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Moving beyond the soil test

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Accepted 10 February 2014; First published online 2 June 2014 **Commentary**

Good research—whether original, incremental or synthesizing—both satisfies with greater understanding of the world's complexity and suggests new questions. This paper does both. It demonstrates that exchangeable K, the standard for evaluating K in soils, does not predict plant available K and that soil testing alone should not guide farmers in nutrient augmentation—yet another compelling reason to review the efficacy of soil testing in an age when excess agricultural nutrients are a major pollution source and cost producers and consumers. But why, after so many excellent pieces of work, is this still an issue? Without belaboring the points made in this paper, I offer Ireland, a small island, as a case study where long-term systematic research identified this problem, formed a consensus and took action.

After World War II, supplementing soil nutrients with chemical fertilizers increased crop yield throughout the industrialized world. Although yield remains an important goal, environmental concerns over excess soil nutrients as well as the economic cost of fertilizer to farmers and consumers have put diagnostic tools, such as soil testing, under the spotlight.

With all the research that has come out over the past 30 years, we can question K fertilizer recommendations based on what we admit is a flawed system. With the research tools now available, we see soil as a dynamic complex interaction of biological, chemical and physical processes. Current soil testing methods look at the chemical aspect while the plant and soil interact symbiotically and are part of another dynamic system called the environment. It is as though a physician relied upon blood tests alone to determine health. Other indicators reflecting more of the soil/plant K relationship over the growing season are needed.

Consider the plant, integrating all the systems, as the final interpreter of what happens in the field. A 6-inch soil sample is only a snapshot of a small part of the root zone where K is taken up. The plant, during the growing season, is a time-lapse motion picture. Sampling a larger area, plants integrate more information about environmental conditions over time.

Schulte's work confirms the important role of plant analysis in nutrient management[1]. Weaver's work on root development in many plants, including corn, showed corn roots one foot deep with a 2-ft radius 36 days after planting[2]. After 56 days, the roots of a single plant explored about 115 ft^3. and at 115 days roots occupied 200 ft^3.

Olson et al.[3] highlighted another weakness in the soil test tool: how different 'philosophies' affect the soil test data, interpretation and fertilizer recommendations. Field experiments over several years on four major Nebraska soils compared corn yields grown with fertilizer recommendation by five soil testing laboratories operating in that state. Economic and agronomic evaluations of the varied approaches on 29 field comparisons revealed no real yield differences despite wide variation in number, rate and cost of the nutrients.

They conclude, 'Since soil test levels are increasing or at least holding steady with the "nutrient sufficiency" approach to soil testing, we find no economic or agronomic basis for the "balance" or "maintenance" concepts on these representative soils of the Western Corn Belt. Not to be overlooked are environmental implications or the waste of energy and resources from any approach responsible for excessive fertilizer use. It is recognized that reserves of available nutrients in the deep subsoils and underlying soil-forming materials in this region have a substantial bearing on soil test calibration and that different calibrations may exist with less favorable subsoil rooting conditions.'

Although Kahn dealt with K, excess N and P nutrients are also environmental problems in the industrialized world. But if we should improve soil testing and other diagnostic tools, such as plant analysis to determine soil nutrient needs more accurately, could we build consensus between the research community, farm advisors and agricultural producers to implement nutrient reduction while maintaining yield? Ireland, relying upon agriculture and its environment to attract tourists, offers a case study.

Irish soils lack available P, limiting plant and animal production. With the memory of famine, agricultural researchers and farm advisors began promoting chemical fertilizers in the 1950s. Farmers, assisted by a government

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subsidy for P fertilizer, had encouraging yields[4] and in the 1960s–70s chemical fertilizer use increased rapidly. The average soil test P increased tenfold: from less than 1 mg l^{-1} using the Morgan Soil Test in 1950 to over 8 mg l^{-1} by the end of the 1980s due to P fertilizer[5]. Phosphorus fertilizer use stabilized at just over 60,000 t yr^{-1} from the early 1980s to the mid-1990s. Since then the trend has been downwards, mainly due to scientific evidence that excess P inputs contributed to pollution of surface waters[5,6]. According to the Irish Department of Agriculture, chemical fertilizer P use is now under 25,000 t yr^{-1}.

Irish agricultural research at Teagasc played a major role in this transition. A 40-year study (The Cowlands project at Johnstown) measured the effects of P on plant and animal production. Animal live weight gain with zero P treatment was about 66% of treatments receiving P. A Morgan's soil test of 4.1–6.4 mg l^{-1} P gave 90–100% of maximum live weight gain (kg ha^{-1} yr^{-1}) in beef animals. Without P augmentation, the concentration of P in grass was 0.2% and doubled when P was applied[7]. Schulte and Herlihy[8] reported on 32 sites over 4 years showing that fertilizer rates to achieve 95% of potential yield were generally low—at Morgan P in excess of 3 mg l^{-1}. Farmers, encouraged by this increased productivity, thought 'if some is good; more must be better' without realizing 'more' could be harmful.

When the Lee River in Cork, a popular tourist destination, turned green in the late 1980s, the public's eye focused. Irish Environmental Protection Agency (EPA) estimated that about half the phosphorus loss to water is from farming. As a result the National Program for Sustainable Development included the goal of reducing P fertilizer use by 10% per year over 5 years from 1997[9]. In addition, a new phosphate regulation was introduced in 1998 to reduce the P content of fresh water to 0.035 mg Pl^{-1} by 2006[9], equivalent to an annual loss of <0.35 kg P ha^{-1}[10,11].

I was involved in analyzing Cowlands data while on sabbatical leave in 1997 and 1998. By that time this research showed excess P as a problem. The Morgan soil test P in the top 0–5 mm portion of soil without P was 5.3 and 51.8 mg l^{-1} for the 30 kg ha^{-1} P treatment[12]. Therefore, the highest concentration of P resides near the top and is most vulnerable to runoff. Tunney[4] demonstrated that farmers were applying much more P than was being removed in crops, animals, milk and water. Furthermore, Ireland was advising more fertilizer P than several other EU countries. Three separate pieces of evidence—crop response, Tunney's balance sheet approach and recommendations used by several other EU countries—all indicated that Irish P recommendations were too high.

Outside the research community there was fierce opposition to these conclusions, particularly from the farm press, fertilizer industry and intensive animal rearing farms (pigs and poultry). Within the scientific community the emphasis shifted from an agronomic issue to an environmental issue. An important step in the process was the International P Workshop (IPW1) organized at Johnstown in September 1995 bringing major world authorities on P together[13]. Then Liam Downey, Teagasc Director, organized a 'Focus on Phosphorus' Conference in 1997 inviting political decision makers to meet with scientists, leading to revisions in the Teagasc P recommendations.

Teagasc and its leadership received abundant criticism for these moves, some from researchers within the organization who had successfully guided earlier P fertilizer work to increase yields. The Department of Environment and EPA may have been influential behind the scenes politically counteracting outside vested interests, while mounting evidence stilled, if not convinced, those within the research community. Political leadership, seeing the threat to precious natural resources, took action. When the EU Nitrates Directive was implemented in Ireland 2006 the Teagasc P recommendations were essentially legally binding.

Teagasc campaigned to change behavior with press, radio and public meetings that offered evidence of the environmental effects of excess P and advised farmers how to bring its use into line with the research. While the farm press and farm organizations continued to criticize, farmers, ever conscious of the bottom line, took this information and acted, almost immediately. P supplements decreased rapidly. In fact, according to Tunney (personal communication) these decreases probably began after the IPW1 meeting. 'No one wanted to be associated with the P campaign up to that point but then everybody wanted to claim that it was their idea and the critics disappeared.' Reducing agricultural P pollution in water is now part of European Union and Irish policy and legislation.

In our own country, we can find examples of efforts by agricultural and environmental science to instruct the community and policy makers to bring about effective change. Wines[14] chronicles phosphorus pollution in Lake Erie, most from agricultural sources and 'the wettest spring on record'. The Maumee River running through Ohio farm country supplies only about 5% of Erie's water but half its phosphorus. Writing in *The New York Times*, he says, 'that summer's algae bloom, mostly poisonous blue-green algae called Microcystis, sprawled nearly 120 miles, from Toledo to past Cleveland. It produced lake-water concentrations of microcystin, a liver toxin, that were 1200 times World Health Organization limits, tainting the drinking water for 2.8 million consumers.'

Like the Lee River, this experience raised public awareness and prompted an urgent call for the 70,000 farmers along the Erie shore to change behavior. Environmentalists raised the cry. Friedman[15] details an Environmental Defense Fund project bringing farmers, scientists and concerned citizens together to address the issue.

'The key question is, how to get enough farmers to practice sustainable agriculture, so that algal blooms and dead zones—whether in Lake Erie or the Gulf of Mexico —become a thing of the past?' she asks. 'The answer lies in convincing farmers that sustainable agriculture is not at odds with high yields and profitability.' In fact, practices such as more efficient use of fertilizer and the creation or maintenance of wetlands and buffer strips, which filter runoff before it can reach streams and rivers, can save farmers money and help improve the quality of their soil.

So let's do this!

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Toward agricultural sustainability through integrated crop–livestock systems. III. Social aspects

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Livestock production on grasslands associated with cereal and vegetable cropping on arable lands was the historical basis of the agricultural revolution that helped shape western civilization during the 16th century in Europe. The process of recycling organic matter and nutrients from livestock feces to cropland and through various fodders consumed by livestock created a relatively closed loop that sustained—and sometimes improved—soil fertility. However, with the advancement of the industrial revolution, particularly in the mid-20th century with widespread use of synthetic fertilizers, reliance on mechanical power for field operations, and improved buildings and equipment for livestock wintering, feeding and milking, interest soon waned for such mixed farming systems. Livestock systems tended to become concentrated to capture economy of scale. Cropping systems became narrowly specialized to capture market opportunities and reduce labor requirements. As a result of these rapid technological changes, livestock production and arable cropping systems became increasingly separated onto different farms—and even in different regions—leading to unusual uniformity of regional agricultural landscapes. Intensification of these two types of specialized agricultural systems has led to unacceptable deterioration of the environment due to: (i) excessive concentration of nutrients and pathogens in livestock production systems; and (ii) loss of natural biodiversity and excessive simplification of ecosystem processes with uniform land use in arable cropping systems.

Facing the necessity to increase agricultural production for a burgeoning human population, it will not be socially and economically acceptable to advocate for a decrease in agricultural productivity just to minimize negative environmental consequences of specialized agricultural systems[1]. Our hypothesis is that by maintaining or enhancing diversity of agricultural systems—at all levels of organization, i.e., the field, the farm, the landscape and the region—it will be possible to reconcile the seemingly dichotomous goals for achieving high quantity and quality of food production and improve environmental quality. Agricultural diversity at the field, farm, landscape and regional levels may need to be simply maintained in less developed regions and improved in various ways and scales in more developed regions[2].

The high capacity of grassland ecosystems for feeding domestic herbivores—and for producing essential ecosystem services, such as CO_2 sequestration, soil fertility, water quality, biodiversity—when associated spatially and temporally with arable cropping systems is an essential foundation for integrated crop–livestock systems (ICLS), either within single farms or among specialized farms within a region. Analysis of ICLS at farm or regional levels requires studies on processes governing biogeochemical cycles, environmental fluxes and dynamics of biodiversity in interaction with management options. In this way, it will be possible to answer the question '*What if...?*' and to evaluate the impacts of systems both in term of production and ecosystem services. Development and adoption of ICLS by farmers implies the need for entrepreneurial evaluation of system types and analyses of socio-economic constraints to answer the question '*What is it necessary for...?*' Hence, advancement of modern ICLS as a concept to promote agricultural productivity and achieve environmental quality will require a multidisciplinary approach

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linking strongly process-based and system-management analyses from local to regional scales.

An international effort to move ICLS forward as an agricultural sustainability concept has been gaining ground through a series of symposia—the first of which was held in Curitiba, Brazil in August 2007 and the second of which was in Porto Alegre, Brazil in October 2012. The first symposium was organized by the Federal University of Parana (UFPR) and was divided into invited oral sessions focused on: (i) the fundamental concept, (ii) the crop component, (iii) the soil component, (iv) the animal component and (v) a worldwide context. Many volunteered posters were also presented, primarily by researchers in Brazil and neighboring Latin American countries, and a tour of research stations and farms in Parana was organized. The second symposium was organized by the Federal University of Rio Grande do Sul (UFRGS) organized into themes of: (i) introduction and summaries of ICLS in different regions of the world, (ii) ecological and environmental processes from fields to landscapes, (iii) issues and tools for integration between livestock and arable cropping systems, (iv) long-term experimental platforms for quantification and prediction of impacts from land use and climate change, (v) management and policies for ICLS at farm to regional levels and (vi) summary comments. Invited speakers came from nine countries, many posters were presented from research being conducted primarily in South America, and a mid-week tour of farms using ICLS principles was organized. From the enthusiasm and success of the first two symposia, a third symposium is already being planned for 2015 in Columbia.

Publication from the first symposium was as proceedings papers on CD-ROM. From the 2nd International Symposium on Integrated Crop-Livestock Systems, we wanted to reach a broader scientific community, and therefore, organized a series of three special issues in international journals under the following general themes:

i. Environmental outcomes (special issue in *Agriculture, Ecosystems and Environment*);
ii. Production responses (special section in *European Journal of Agronomy*);
iii. Social aspects (special section in *Renewable Agriculture and Food Systems*).

Five papers from the symposium in Porto Alegre are presented in this issue and summarized in the following. Coquil et al. outlined an approach aimed at understanding the transition to autonomy in mixed crop–livestock systems with progressive mobilization of external inputs and acquisition of experience through trials and problem solving. New ways of thinking and acting by farmers were developed by mobilizing various resources, some of them shared: introducing rotational grazing, diversifying the winter diets of the dairy cows and diversifying the composition of the sown pastures. In spite of sharing resources, operation of many farms is still unique; requiring reliance on various internal resources available on the farm.

Torre and Darly analyzed the role of territorial governance, which is the engine of local development, and the tool for better local compromises, involving periods of opposition and streams of negotiation to help overcome conflicts and tensions at the interfaces of rural, natural and peri-urban areas. This evaluation of conflicts in land use within a peri-urban context was based on studies in the Greater Paris region, and a case study on the use of agricultural soils on the urban fringe.

Poccard-Chapuis et al. used historical changes in Southern Mali, Brazilian Cerrados and the Amazon frontier to illustrate the potential for greater crop–livestock integration in the tropical region. Spatial and social arrangements of integrated systems were characterized within a landscape context. This approach provided a retrospective view to discuss four key points about the future of integrated systems in the tropics: (i) importance of landscape structure for design and adaptation of the integrated systems; (ii) key role of local institutions in supporting such integrated systems; (iii) trade-offs between external and internal resources; and (iv) role of nitrogen to improve system efficiency.

Oliveira et al. determined the economic responses of different grazing intensity levels of winter pastures in a long-term experiment in Rio Grande do Sul, Brazil. Soybean yield was not affected by grazing intensity, but cattle's average daily gain declined with increasing grazing intensity, cattle gain per hectare increased with increasing grazing intensity and gross margin was optimized when grazing intensity was moderate (i.e., sward height was between 10 and 20 cm). The ICLS improved economic performance compared with grain cropping only.

Duru et al. proposed a conceptual framework based on plant functional traits to better describe interactions of diverse agricultural components on community structure responses to disturbances and resources, as well as to define their effects on ecosystem functioning and services. The approach was used in grassland-based livestock farms in France to predict forage provision and non-market services according to environmental and management drivers. Environmental gradients were weakly predicted, while soil microbial functional traits need to be developed. An adaptive management approach was suggested rather than relying on a prescriptive scheme.

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We also thank the participants of the symposium for bringing up their ideas for discussion. We thank the authors of these papers for working diligently to assemble high-quality contributions and we thank the many reviewers who devoted their time and expertise to note deficiencies in presentations and to suggest improvements. We hope that this set of special issues is the beginning of fruitful research and development among scientific colleagues and with industry partners to improve agriculture for the benefit of humankind.

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Transition to self-sufficient mixed crop–dairy farming systems

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Abstract

While plains favorable to agriculture are still dominated by specialized and intensive agriculture, self-sufficient mixed crop-dairy farming systems increasingly attract policy makers' and scientists' attention. Owing to their limited use of purchased inputs, they can contribute to reducing the environmental impact of agriculture. Furthermore, self-sufficient farming tends to be linked with a search for autonomy in decision-making, i.e., farmers developing their own technical reference framework. Such farming systems can thus also contribute to alternative development pathways of rural territories. In this paper, we analyze how ten intensive mixed crop–dairy farms have progressively evolved toward more self-sufficient and autonomous systems. Through formalizing farmers' transition *in action,* we identified 34 tools that the farmers implemented making them reflect on their farming system, shift socio-professional networks, reorganize work routines, and steer the evolution of their production practices. For example, they created temporary pastures in crop rotation, introduced rotational pastures, observed their herds to adjust their feed and keep the animals in good health, and they limited expenditures to manage their cash flow. Which tools were used and when they were used depends on what is meaningful to them at various stages of the transition. Our analysis of transitions *in action* has three original features: it is centered on the transition as perceived by the actors who experience and manage it; it proposes a long-term conceptualization of the dynamics of farming systems, based on the farmer's initiative and creativity; and it highlights tools implemented by farmers during the transition to self-sufficiency and autonomy.

Key words: autonomy, self-sufficiency, mixed crop–dairy systems, transition

The Potential Role of Mixed Crop–Livestock Farms

Systems of mixed crop–dairy farming are crucial to world food security[1]. French policy makers[2] as well as the scientific community[3] are focusing especially on mixed crop–dairy farming that is self-sufficient. Such farms are an archetype of agronomic coherence, e.g., within organic farming systems[4,5]. Mixed crop–dairy farms that are self-sufficient (i.e., require little off-farm, purchased inputs) and are autonomous (i.e., guided by farmers who have developed their own technical reference framework) have proved their sustainability in several respects: socially[6], environmentally[7] and economically[8–10]. In France, this approach to farming was promoted by a technical and political movement that started in the 1970s[6]. Autonomous farmers strived toward farming with very few synthetic inputs (if any), and emphasized the necessity to create their own technical reference framework. This necessity was justified by the local and situated nature of knowledge and resources in systems using few inputs[11], and by these farmers' wish to 'extricate themselves' from the norms and technical constraints conveyed by the prevailing farm advisory services. Despite this early start, the number of mixed crop–livestock farms is diminishing, reflecting the overall trend of ongoing specialization of farms and the consequent increase in the use of inputs[12]. Yet, there are a number of mixed crop–dairy farmers who are interested in strengthening their autonomy, not least through implementing a self-sufficient farming system. Supporting this interest through research results can help to develop farming systems that contribute to the sustainable development of rural territories.

A number of multidisciplinary studies have analyzed processes of transition toward self-sufficient farming systems (e.g., [13,14]). In a review of the topic, Lamine and

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Bellon[13] have shown that such studies focus primarily on transitions *a posteriori*. For example, the theoretical framework of Hill and MacRae[14] characterizes the depth of changes made, from the experts' point of view. However, it barely documents the processes that farmers implemented *during* the transition process, nor the farmer's reasons for selecting specific changes. The aim of our research was to analyze transitions *in action*, and to develop a theoretical framework that allows analyzing the transition process from intensive crop–dairy farms that use significant amounts of purchased inputs, toward crop–dairy farms that are self-sufficient in inputs.

Our focus in analyzing transitions *in action* is on the resources that farmers actually mobilize during the transition, i.e., identify which resources and tools farmers use. This will allow us to formalize them, and to make them available to intensive crop–dairy farmers who wish to transform their system toward more self-sufficiency and more autonomy.

We used the 'Instrument Mediated Activity'[15–17] as a theoretical framework to conceptualize the notion of 'instrument'. The theory allows us to highlight three important aspects of instruments: that instruments need to be seen as embedded in a historical context; to point out that instruments are always a coupling of a tool and a human dimension; and to differentiate an instrument from the outcome that is to be achieved through using it. Within Instrument Mediated Activity, the concept of an 'instrument' is drawn from the international research stream of historico-cultural approaches to activity (see for e.g., [18]), whose main argument is that human beings are faced with an environment that has many dimensions designed or produced by humans themselves and that influence their functioning and transform them. From this perspective human activity, especially what they do when they are working, is a historical construction that cannot be separated from the instruments used. Consequently, the instruments themselves enable us to analyze transition processes and changes of farming practices.

Yet, when focusing on instruments, the theory of Instrument Mediated Activity points out that an instrument is a 'coupling' between a technical resource and the use to which it is put. For example, a monkey wrench is not an instrument *per se*; it is only a tool. Depending on the use to which it is put, it can unscrew a nut, or serve as a hammer. Another simple example is a chair: it can be used to sit on but also to stand on so that one can change a lightbulb. An instrument is therefore a compound entity: it always consists of a tool—which can be either a material tool (e.g., a chair) or a cognitive tool (e.g., a procedure, a graph)—and of a way of doing things, *a human dimension* related to how the tool is used. It is this association between the tool and the human dimension that constitutes the instrument (for a detailed conceptual discussion, see in particular [16,17]). Insofar as the instrument is a combination between these two dimensions, analyzing the instruments that appear during transitions in farming systems cannot be reduced to tools, i.e., artifacts. It is also necessary to examine the use to which they are put: the ways of doing and thinking that farmers associate with the tools they employ.

Furthermore, Instrument Mediated Activity highlights that an instrument is finalized, insofar as the farmer's intention is not to interact with the tool itself. An instrument can thus not be analyzed as something autonomous, but must be understood in relation to the final purpose to which it is put. More precisely, the purpose of the instrument is to act on or to transform an object to achieve an outcome. For example, word-processing software (a tool) can be used as an instrument to prepare a political speech (an object) the purpose of which is to ensure that the speaker is elected (an outcome). The notion of *object* thus defines that on which a person acts to achieve an outcome[19].

When analyzing a transition from intensive to self-sufficient farming systems, several elements need to be distinguished, although they are all closely interwoven: the instruments (tools and ways of using them) that farmers select to act on agronomic entities (objects), with the purpose of achieving a desired outcome. In this analysis of a transition *in action* we will focus on answering two questions: which *tools* do farmers use to transform their intensive mixed crop–livestock farm into a more self-sufficient system? And on what *objects* do mixed crop–dairy farmers act during this transition toward self-sufficiency?

We will first present the network of farms we studied and the methods used for collecting and analyzing the data. We will then present tools we identified and how farmers used them during the transition. We will also identify a particular category of tools: the key tools of the transition. In the last part, we discuss the interest of an analysis of transitions in action.

Materials and Methods

We used a case-study approach and thus focus on the in-depth study of ten cases. This allowed us to study each case within its context to understand the specificities and history of the situation[20,21]. This inductive approach[22] allowed us to analyze singularities and detect patterns, before formulating hypotheses regarding tools and objects. We explored these further before formulating some general issues and principles.

Ten mixed crop–dairy farms

Ten mixed crop–dairy farmers were selected, nine commercial farms and an experimental farm. The farms were selected to cover a diversity of area devoted to cash crops (excluding maize silage): between 0% and more than

Table 1. Characteristics of the ten mixed crop–dairy farms included in the study.

Farm no.	Area (ha)	No. of dairy cows	Imported nitrogen[1] ($N\ ha^{-1}\ yr^{-1}$)	Organic	Worker or group of workers	Intensive past	Categories of activities	Sub-categories for 'dairy' and 'mixed crop–dairy farming'
RAD1	183	95	60.5	No	A1	Setting up	Dairy farming	Supplementing
					A2	Zero grazing	Crops	
					A3	Zero grazing	Dairy farming	Grazing
RAD2	260	100	33.9	Yes	A4	Setting up	Crops	
					A5	Setting up	Dairy farming	Supplementing
					A6	Grazing	Direct sale	
					A7	Grazing	Mixed crop-dairy	Self-sufficient
RAD3	32	25	11.8	Yes	A8	Zero grazing	Dairy farming	Grazing
RAD4	74	41	2.1	Yes	A9	Grazing	Dairy farming	Grazing
RAD5	106	38	50.8	No	A10	Grazing	Administration	
					A11	Grazing	Mixed crop-dairy	Self-sufficient in dairy, low-inputs for crops
RAD6	47	44	0.7	Yes	A12	Zero grazing	Dairy farming	Supplements
RAD7	107	66	46.2	No	A13	Grazing	Mixed crop-dairy	Self-sufficient in dairy, low-inputs for crops
RAD8	145	70	25.9	No	A14	Zero grazing	Mixed crop-dairy	Self-sufficient in dairy, low-inputs for crops
RAD9	153	76	NC	No	A15	Zero grazing	Mixed crop-dairy	Self-sufficient in dairy, low-inputs for crops
INRA	160	60	1.1	Yes	A16	Grazing	Mixed crop-dairy	Self-sufficient

[1] Imported N = N mineral + (0.65 or 0.75) × N imported fodder (concentrates, forages) ± importation/exportation N organic[23].
In this equation:

- N mineral = imported nitrogen in mineral fertilizers.
- N imported fodder = imported nitrogen in bought food × 0.75 (for ruminants) and imported nitrogen in bought food × 0.65 (for monogastric animals) (0.75 because 25% of N intake is valorized by ruminants and 35% of N intake is valorized by monogastrics animals: the rest of N stays on the farm in slurry, manure or is lost by atmospheric emissions or leaching in water).
- ± importations/exportations organic N: compost, manure, etc.

50% of the Utilized Agricultural Area. The selection also included differences in experiences, e.g., with regard to grazing of dairy cows. The ten farms also cover a range of farm types regarding ownership, management and workforce: individual farmers, couples and shared ownership (Groupement Agricole d'Exploitation en Commun—GAEC) with or without employees. As the farms are not necessarily homogeneously managed, we distinguish between 16 workers or group of workers which each act differently in the farm (Table 1). All ten farms had been managed intensively (i.e., based on a high reliance on purchased synthetic inputs) before gradually changing their practices to use fewer synthetic inputs and striving to become self-sufficient. We characterized the reduced use of these inputs using an indicator of imported nitrogen[23]. In 2010, the ten farms imported between 0.7 and 60.5 units of nitrogen $ha^{-1}\ yr^{-1}$.

The nine commercial farms belonged to a sustainable agriculture network called the *Réseau Agriculture Durable* (RAD), a federation of farmers wanting to develop their autonomy, i.e., create their own reference framework, focusing on ways to reduce their purchases of farming inputs and eventually becoming self-sufficient. Autonomy and self-sufficiency correspond to the implementation of farm management based on the notion of stewardship, i.e., 'a good family father' (a '*bon père de famille*'[6]). This form of management is characterized by a cautious approach, using a minimum of cash expenditures, implementing the precautionary principle by limiting the use of potentially polluting inputs (chemical fertilizers, pesticides, etc.)[7].

The tenth farm was the experimental farm managed by the INRA ASTER-Mirecourt research unit. An area of 240 ha was converted to organic farming for the purpose of designing two systems requiring very few inputs: a grassland dairy system and a mixed crop–dairy system. These two systems, set up in 2004, were designed progressively, in a step-by-step fashion to allow learning from experience. The experimental approach focused on ongoing improvement aimed at solving the technical difficulties encountered along the way and reinforcing the self-sufficiency of the systems[24]. This experimental approach was designed and implemented by a collective (i.e., farm employees and researchers). The collective used to manage the experimental farms intensively in the early 1980s and more extensively until 2004, when the conversion from conventional to organic farming was initiated.

Analysis of the activity of mixed crop–dairy farmers

We collected data to characterize the work of the farmers and to analyze the development of this work, starting from the initial, more intensive farming practices. The data were collected through a series of three interviews with farmers over a period of a year and a half (from February 2011 to September 2012). The first introductory interview used the open interview technique[25]. During this first interview, we discussed the definition of mixed crop–dairy farming from the farmers' point of view, and the difficulties in establishing a self-sufficient system. The second and third interviews were based on the elicitation interview technique[26], which allows it to remain as close as possible to the action underway. This enables the identification of individual actions and their determinants as they take place, and not as an *a posteriori* analysis. During the second interview, we focused on a description of the course of the 2010 agricultural campaign, i.e., the last agricultural campaign that had been completed at the time of the interview. The analysis of this interview was designed to formalize the farmers' work on their self-sufficient mixed crop–dairy farms in 2010. This formalization was inspired by the conceptual structure of situations as defined by Pastré[27] and Caens-Martin[28,29]: a representation shaped around farmer's objects and daily indicators to act in his farm. Based on formalizations around different objects, 16 formalizations of the activity of the autonomous and self-sufficient mixed crop–dairy farmers emerged (Table 1). These 16 formalizations correspond to the activity of individual farmers or groups of farmers mainly depending of farms' collectives and work organizations. The third interview was mostly used to validate the analysis of the first two interviews and assess in which order the tools were used. We thus asked the farmers to go over the steps and events in the transition toward self-sufficiency in inputs, which were identified through the analysis of the data from the first interview. We also asked them to review the practices and indicators that they used in 2010, which we identified through the analysis of the second interview. The analysis of this third interview focused on the chronological order in which the tools were used during the transition, on their instrumentation (i.e., how the tools were integrated into farmers' agricultural practices), and on the agricultural objects that appeared or were transformed during the use of these tools, in the farmers' activity during the transition.

On the INRA ASTER-Mirecourt experimental station, data were collected through interviews with the farm managers, through group interviews and individual interviews with farm technicians. Active participation of one of the authors in the design of the farming system also served as a source of data. The data were then used to identify the objects of experimenters of this experimental farm in 2010, as well as their development since 1973.

The data collected through the interviews were analyzed case by case and a monograph was written on each case. These ten monographs were then used as material for the transversal analysis. This analysis focused on the tools used by farmers during the transition, the objects transformed during the farmers' activity by the use of these tools, and the agricultural practices adopted during the transition. The aim of the analysis was to compile an inventory of tools that farmers integrated into their agricultural practices during their transition toward self-sufficiency in inputs. Tools were thus grouped based on the agricultural object that was transformed through the farmer's use of the tool.

Based on this inventory of tools, we defined the key tools by analyzing their function on the agricultural objects (e.g., animals, crops and economics). The key tools were those that brought to the fore new objects in farmers' activity during their transition toward self-sufficiency. The appearance of new objects revealed the adoption of new operational and cognitive approaches by the farmers, which restructured their work. We thus distinguish between key tools, which brought forth new objects, and tools which modified or consolidated objects which already existed in the activities of farmers.

The other purpose of the analysis is to understand the dynamics of the use of these key tools during the transition. We therefore focus on the effects of the original system, on the categories of activities in 2010, and on the chronology of the application of key tools during the transition. Three groups of original systems, that is, the intensive mixed crop–dairy system which existed before the start of the transition process, were distinguished. Some farmers used pastures to provide grazing for dairy cows, some did not use pastures and two farms were set up directly as a system that was self-sufficient (Table 1).

The categories of the activities were defined on the basis of objects. Four categories emerged: one revolving around dairy farming, another around mixed crop–dairy farming, a third around direct sales and a fourth around administration (Table 1). The category 'dairy farming' had two sub-categories: 'supplementing', consisting of farmers who focused on dairying and who gave their cow's supplements so as to be as reactive as possible to their health and physical condition. The second subcategory was 'grazing', consisting of farmers who used grazing as the (almost) exclusive means of feeding their cows. The category 'mixed crop–dairy farming' also had two sub-categories: 'self-sufficient', encompassing farmers aiming for self-sufficiency in inputs for both their crops and their cows; and 'self-sufficient in dairy and low-input in crops', consisting of farmers who aimed at being self-sufficient in inputs for dairying, but who only aimed at reducing their inputs for their cropping.

Table 2. Key tools mobilized by farmers to steer their farming systems toward self-sufficiency.

Agronomic objects	Action of the tool on the object	Mobilized tools
Animal	Manage diet/animal health	Obsalim® training
Crops	Limit weed with less (without) herbicide	Organic agriculture and non-use of chemicals Environmental contracts, temporary grasslands, equipment, rotation grazing (Pochon method)
	Prevent crops accidents	Posipré
	Produce seed on farm	Seed production
Economy	Limit waste of equipment	Fixed cost accounting
	Limit expenditures	Gross surplus/farm product
	Reassuring himself about economic performances of self-sufficient systems	Economic scenarios
Balance of matter	Adjust animals' needs/fodder and concentrates production	Livestock number, diet equilibrium, equipment, stocks with less maize silage
	Adjust straw needs/production	Need of straw diversification of cultivated species
Fodder	Feeding with grass	Stocks with less maize silage, green forage feeding
	Manage diet/animal health	Obsalim® training, rotation grazing (Pochon method)
	Manage grazing	Rearrangement of paddocks, implantation of temporary grasslands, grouped field, rotation grazing (Pochon method)
	Introduce temporary grasslands composed of legumes in cultivated fields	Diversification of the composition of temporary grasslands, implantation of temporary grasslands
	Organize rotational grazing	Rearrangement of paddocks
	Secure fodder during drought periods	Rotation grazing (Pochon method), drought
	Secure fodder stocks	Drought
Equipment	Adapt equipment	Equipment
Observations	Diagnose illness to treat	Organic farmers' organizations
	Observe crops	Organic agriculture and non-use of chemicals
	Learn	Experience of older farmers, commercial networks, organic farmers' organizations, RAD
Potential	Adapt cropping plan to field potential	Diet
	Adapt fertilization to the needs	Soil analysis
	Spread compost on grasslands	Compost
Productivity	Increase crop productivity	Land planning, stocks with less maize silage, implantation of temporary grasslands, renewing grasslands
Socio-professional networks	Open to society	Discussions/contacts with customers, agricultural syndicate
Work	Manage diet/animal health	Obsalim® training
	Organize work	Association of species and varieties, crop rotation
Sales	Direct sale	Discussions/contacts with customers

Results: Tools and Practices of the Transition

During their transition toward autonomy in decision-making and self-sufficiency inputs, farmers use a variety of tools. When used, these tools become the instruments of the farmers' action. This encounter between usage and the tool transforms not only the tool but also the farmers' practices, by revealing or modifying the objects of their work. Hence, the usage of tools induces a change in the objects on which farmers act to do their work. This dialectic between tools and usage spawns the instrument or the 'application of the tool', which is always singular. We will focus more particularly on the 34 key tools (Table 2), that is, the tools whose use reveals new objects on which farmers act during the transition. We then examine the singular nature of an instrument consisting of the same tool used by several different farmers. Finally, we analyze the explanatory factors and chronology of mixed crop–dairy farmers' mobilization of the key tools.

The key tools of the transition to autonomy

The farmers mobilized a total of 43 tools. We have sorted these tools according to the objects on which the farmers acted when they used the tools. Thirteen agronomic objects appeared, were modified or lasted under the effect of the farmers' use of the tools: animals, crops, economics, employment, balance of matter, fodder, equipments, observations, potential, productivity, socio-professional networks, work and sales (Table 2). The use of 34 of these 43 tools by farmers resulted in the appearance of new objects structuring the farmers' activity during

the transition. In the transition to autonomy and self-sufficiency in inputs, it acted on all the agronomic objects of the transition, except employment. We will now discuss the tools that were used on the 12 identified objects, and the reasons farmers used these tools.

Farmers act on 'fodder'using 14 tools, 9 of which played a key part in the evolution of the farmers' work during the transition (Table 2). Some farmers reduced stocks from maize silage, and increased the proportion of grass in their animal feed by more use of grazing and green forage feeding, and by building up stocks from grass (hay, silage, etc.). They introduced or changed their pasture management by means of rotation grazing, which in the RAD Network is called the 'Pochon method'. It consists of temporary pastures with mainly raygrass and white clover, where cows are left for 3 days on the paddocks, and the grass is then left for 35 days to grow back. The introduction of rotation grazing sometimes required a rearrangement of paddocks, such as the planting of hedges to provide the animals with shelter, the creation of paths, or exchanges of fields so that they were accessible to the cows. Rotation grazing was also used by some farmers to deal with animals' health problems (e.g., problems of tonicity of dairy cows that are calving). Farmers who had been trained in the Obsalim® [30] method for diagnosing their animals' health problems and the relationship between health and food, changed their forage system by granting more importance to the distribution of stored forage. The diversity of the stocks built up (alfalfa hay, multi-species hay, etc.) and the availability of stocks as supplements, including during periods of grazing, was increased. Starting off with the creation of temporary pastures with raygrass or white clover (Pochon method) in rotation grazing, farmers sometimes diversified the composition of pastures, depending on the type of paddocks (cocksfoot was often introduced in dry paddocks) and on the use of the pasture. The mixture based on raygrass and white clover proved difficult to dry in the form of hay. The creation of these temporary pastures of grass and legume fodder crops was also intended to improve the nutritional quality of the fodder harvest. Periods of drought and the wish to ensure fodder security in the summer led the farmers to test and then integrate new fodder species that grow in limited rainfall conditions, such as alfalfa and fodder sorghum. Fodder security in times of drought was achieved partly though the increase and diversification of fodder stocks. Occurrences of drought in spring, summer and autumn prompted farmers to multiply fodder resources in order to constitute stocks in all periods of water stress (mixed cereal and legumes crops, fodder corn, sorghum, intercrops, etc.).

Seven key tools of the transition enabled farmers to act on crops. Those who had converted to organic farming or entered into a *Contrat Territorial d'Exploitations* (part of the French agri-environmental program) such as the *Système Fourrager Econome en Intrant* (low-input fodder system), limited the use of pesticides on field crops. They consequently also extended and diversified their rotation, and used new farm equipment such as hoeing machines, maize sowers with localized herbicides sprayer and weeding harrows. These tools reduced the pressure to use herbicides yet allow weeding of crops. By creating temporary pastures in crop rotation they limited weeds and thus the use of herbicides. Alfalfa for instance, tends to clear grasslands of thistle; maize fields tend to be clear of weeds after ploughed grasslands; and grazing tends to have a cleaning effect on temporary pastures, which limits dock populations in crop rotation. One of the farmers used the Posipré method build by Patrick Saulas to diagnose diseases on cereals. This diagnosis led him to discover that mixed-variety cereals tend to be less prone to disease, which enabled him to avoid spoiled crops while limiting the use of fungicides. Finally, the farm production of seed for cereals, corn, fodder grass and legumes is a key tool that enabled several farmers to achieve economies of inputs (seed) during the transition period.

Farmers used six key tools having an effect on balance between fodder needs and what could be produced on-farm, they adjusted the livestock numbers in relation to available fodder; they adjusted winter diets of the various batches, based on fodder available on the farm (stocks with less maize); they adjusted the composition of winter diets close to the protein and energy balance, by having less maize silage, more hay, and grass silage; and they used grain crushers and oil presses to produce farm concentrates. The farmers acted on the balance between straw needs and availability by limiting the needs. They did so by replacing straw with poor-quality hay for litter, and by increasing the productivity of cereal straw by planting varieties such as rye and wheat with a high straw yield.

Farmers used six key tools making them devote time to observation and develop their skills and autonomy. They participated in training organized by *Groupements d'Agriculteurs Biologiques* (interest groupings of organic farmers), mainly on how to care for animals. This raised farmers' level of vigilance so that they could diagnose 'abnormal' states of their animals and be able to provide them with care rapidly. Farmers also observed the development of their crops, so that they could intervene when necessary (e.g., interseeding with another crop in case of problems of raising) or else not intervene (e.g., not destroy regrowth of rapeseed and thus leave it in place for a second crop year) without any risks of persistence of pesticides. The experience of older farmers, interaction within groups of farmers in the network of sustainable agriculture, and exchange between organic farmers all afforded opportunities to compare the findings and lessons learned by each of them, and thus to increase their knowledge and apply it on their own farm.

Farmers stabilize or increase the productivity of crops using four key tools: changing the land use to include as many fields of the farm as possible in rotations with

temporary pastures; mixing crops of wheat and legumes (e.g., peas, horse-bean) to rival the productivity of maize silage; renewing pastures to maintain the flora and their productivity by introducing productive varieties such as red clover and hybrid raygrass; and working on temporary pasture sowing practices to ensure their raising and limit their spoilage by weeds (seeding combined with oats).

Farmers work on their farm economics using three key tools: fixed cost accounting (allowed if annual economical product stays below 76,000€) was used by one couple to pay set social welfare contributions from 1 year to the next and thus avoid the temptation that farmers who opt for actual cost accounting have, of making too many tax-deductable investments in the farm. Their investments were thus guided by the necessity for farm equipment and not by the necessity to create charges to obtain tax deductions. This limited the replacement of equipment that had not been used, and thus limited wastage. The ratio of gross surplus to farm product is a commonly used indicator of the economic efficiency of a farm. The discovery of a ratio that could attain 50% made one of the farmers aware of the economic performance of systems that were self-sufficient in inputs. He consequently studied their functioning with a view to limiting expenses on his own farm. This farmer also built several scenarios of reduced inputs on his farm, which enabled him to evaluate their economic performance and thus to reassure himself before actually making changes.

Some farmers adjusted their work organization by mobilizing three tools during the transition. First, the farmers who applied the ruminant feeding principles learned during the Obsalim® training organized their work by splitting up and ordering the distribution of meals to their dairy cows. One of the farmers combined peas with a cereal which gave the pea plants support and thus facilitated the harvesting of the latter. After this initiative he engaged in the regular large-scale use of such combinations. Farmers with a farm consisting of sites over 15 km apart organized their long rotations by giving particular importance to logistics during the harvesting of fodder and the spreading of manure.

Field potential became an object of farmers in transition, through the use of three key tools. Two brothers revised their animals' diets so that they could adjust the land use to its potential and not to the diets that they wanted to give. They created pastures on lands that were difficult to cultivate. Some farmers analyzed the soil to adjust basic fertilization to the needs and potential of the land, and thereby to stop systematic fertilization. One farmer composted part of his manure to fertilize pastures with farm fertilizers and thus to limit the purchase of mineral fertilizers.

Discussions and contacts with customers and participation in an agricultural syndicate were valuable tools mobilized by farmers, which afforded them contact with society. This contact helped to reassure them with regard to their choice of self-sufficiency for their farm, as the low use of synthetic inputs converged with society's expectations. Deliberate choices of this kind can be difficult for farmers to live with in an agricultural world in which the consumption of inputs prevails as a form of security and a way to optimize yields.

Farm equipments are a key tool mobilized by some farmers in the transition to autonomy. Farmers grant importance to the choice, the tuning and the transformation of equipments for sowing, mechanical weeding and working the soil, so that they can adjust these tools to the conditions in which they want to use them. One farmer created a seeder enabling him to sow broadcast large quantities of cereal seed in a field under a crop cover.

Only one key tool was mobilized by farmers to act on their animals during the transition: the Obsalim® training. The ways in which this training was used are detailed in the following section.

From tool to singular uses: the instrument

Each of the tools can be mobilized by farmers during the transition to self-sufficiency, thus contributing to their decision-making autonomy. Farmers' usage of these tools is anchored in ways of doing things, in whatever is meaningful to them in their ways of working and in the context in which they work. This always results in singular instruments that we we will consider through the use of the key tool of the transition period, mobilized by mixed crop–dairy farmers to act on their animals: the Obsalim®[30] training.

Integration of the Obsalim® training and its application by autonomous mixed crop–dairy farmers was concretized in several instruments. Some farmers systematically distributed 'fibrous' or 'mechanical' hay at the beginning of the morning or evening meal to stimulate the animals' salivation and thus create a buffer for the pH of the rumen. The Obsalim® training encouraged other farmers to organize their work around a divided distribution of meals, so that the cows could be left to eat the fiber and only afterwards be given foods with a higher energy value. After this training several farmers multiplied their observations of the animals (consistence of dung, licking on shoulders, number of shot jaws by mouthful ruminated, etc.), alone or in a group through '*rally poils*' (name of the group observing cows and especially their appearance), in order to assess their well-being and their health. These observations enabled them to diagnose the cows and to adjust diets and meals accordingly, with a view to improving their health. Farmers thus generally preferred the diversity of available fodder in stock to make up meals. They gave significant quantities of fibrous foods and, from a qualitative point of view, recognized the advantages of maize silage for limiting gastric reflux in the cows during turn out to grasslands. This enabled them to maintain the physical health of their dairy cows. Starting from the same tool, the Obsalim® [30] training, farmers

learn about the relation between diet and animal health. The different instruments developed depended on several factors: interest of farmers to health management, the diversity of forages they have to adjust the diets—the main factor explaining different instruments was the genesis it promoted in the farmers' activity. For some farmers, the use of that tool created new objects, like the coupled management of diet and health, changing many practices, like the different forages that are cultivated on the farm. For other farmers, the use of that tool just made practices move or appear, like the systematic distribution of hay at the beginning of every meal.

A sequence in the use of key tools?

This analysis highlights the progressive nature of the transition, that is, the step-wise changes in the agricultural system. Such gradual change raises the question of the existence of a chronology in the mobilization of the tools, whether the tools appear in a set sequence during a transition toward self-sufficiency. We first examine this chronology in relation to the farmers' past and then we examine it according to the structure of their activity in autonomous and self-sufficient systems in 2010.

Three of the 16 farmers or farmers' collectives (Table 1) settled on an autonomous self-sufficient mixed crop–dairy farm. Two of these farmers were engaged in the transition to autonomy, and mobilized older farmers' experience to this end. The third farmer had chosen to settle on an autonomous farm because of the appeal that grazing cows had for him. His application of the Obsalim® training very quickly caused him to depart from the technical choices of his experienced partners. Aware of the link between animals' food and their health, this new partner chose to increase the quantity of stored fodder and the concentrates distributed, so that he would be able to give his cows supplements, including during grazing periods. This way of ensuring fodder security by stocking, which was very different to the maximization of grazing that his partners had opted for, was reinforced during drought periods. Chronologically, the first two farmers drew on their experienced partners' know-how as soon as they started farming. They applied this experience in practice, thus gradually transforming it into their own experience (notably with regard to managing grazing and to combinations of cereal and high-protein crops). One of these two farmers subsequently applied the knowledge acquired in the Obsalim® training, which led him to more finely adjust his herd's feeding plan that his predecessor had implemented.

Before their transition, seven farmers or farmers' collectives out of 16 worked in systems of intensive mixed crop–dairy farming with a grazing herd. These farmers mobilized various key tools for their transition to autonomy and self-sufficiency in inputs. The tools enabled them to work on new objects pertaining to the animals, the crops, the farm economy, balance of matter, fodder, farm equipment, observations, potential of fields, the farm's productivity, work and sales. The mobilization of key tools and the objects structuring these farmers' activity during the transition did not seem to be closely related to their past when they practiced intensive farming with grazing. On the farms of three of these seven farmers or farmers' collectives we witnessed the structuring of a reduction in the use of herbicides and, more broadly, pesticides on large crops, which mobilized key tools such as the signing of a *Contrat Territorial d'Exploitation*, engagement in organic farming and rotation grazing on temporary pastures in order to limit weeds in the fields during the rotation. For three of these seven farmers the work on grass became a structuring feature of their activity: management of the rotation grazing, creation of pastures with pulse crops in the rotation, and the constitution of stocks without maize silage changed their ways of working their farms. These farmers' past experience in intensive farming with grazing did not seem to affect the order in which they mobilized their key tools during the transition.

Six farmers or farmers' collectives out of 16 worked within systems of intensive mixed crop–dairy farming without grazing for their dairy cows. The key tools that they used during their transition also varied widely and caused them to work on new objects concerning their animals, crops, farm economy, balance of matter, fodder, observations, potential, productivity, socio-professional networks and work. Yet with these six farmers or farmers' collectives the work on fodder structured the activity, from the beginning of the transition. They started by rearranging their parcels of land into groups, planting hedges, building paths and then creating temporary pastures before starting rotation pasture management or green forage feeding. Later on in their transition they worked on diversifying fodder by planting diversified pastures or sward that could serve for grazing (sorghum) or that could be harvested (intercrops) to ensure the security of the fodder system.

We now examine chronology of transition according to farmers' activity in their autonomous and self-sufficient farming system in 2010.

Two farmers or farmers' collectives out of 16 structured their activity around mixed crop–dairy farming with the aim of achieving autonomy and self-sufficiency in inputs for their crops and animals. During their transition to autonomy, their activities were structured around new objects pertaining to crops, equipment, field potential, balances, farm productivity, work and observation. For these farmers observation was the new object that appeared during the transition. They observed and experimented with new techniques for managing crops without pesticides. This opened new perspectives: not acting and letting nature do its job, or intervening as soon as they wished to since there could be no side-effects of pesticides.

Four of the 16 farmers or farmers' collectives focused on mixed crop–dairy farming and aimed for autonomy in

inputs for their dairy farming and a reduction in the use of inputs for their crops. During the transition to autonomy, their activities were structured around new objects pertaining to economy, balance of matter, fodder, field potential, productivity, socio-professional networks and work. From the beginning of the transition these four farmers worked on fodder: three of them set up and optimized rotation grazing, and the fourth one sowed grass and valorized it through green foraging.

Three farmers or farmers' collectives concentrated on dairy farming in their system of autonomous and self-sufficient mixed crop–dairy farming. They departed from a system of grazing exclusively and gave the animals supplements. During the transition to autonomy their activities were structured around new objects pertaining to the animals, crops, fodder, observation and work. The three farmers mobilized the Obsalim® [30] training. This opened perspectives for them regarding animal management and fodder management during the transition. Whereas they had started their transition with work on rotation grazing, the appearance of the link between food and animal health caused them to depart from grazing alone. They supplemented their animals' food by a variety of fodder, including during grazing periods.

Three farmers structured their activity in autonomous and self-sufficient systems around dairy farming, concentrating their feed diets on grazed grass. During the transition to autonomy their activities were structured around new objects related to animals, crops, balance of matter, economy, fodder and productivity. The arrangement of parcels of land and the setting up and management of rotation grazing were highly structuring in the transition of these three farmers or farmers' collectives. They started the transition with work on fodder by mobilizing these tools.

Finally, two farmers structured their activity in autonomous and self-sufficient systems by focusing on crop management. During their transition to autonomy and self-sufficiency in inputs, their activities were structured around new objects relating to crops, fodder, observations, socio-professional networks and sales. Their openness to others' experience so that they could ask them questions and thus enrich their own experiences in contact with their predecessors or peers did not take place at the same time and did not have the same functions. The first farmer was experienced, and interaction with his peers took place when he was already engaged in change. They reassured him with regard to his choices. The second farmer was a novice and training was his first key tool; it enabled him to make contact with his predecessor.

Discussion and Conclusion

This study proposes a formalization of the transition of agricultural systems *in action*. We approach the transition by way of its contents: we formalize the key tools that farmers mobilize to change their practices, and the objects concerned by that change. We also examine some explanatory elements of the chronology of mobilization of tools by farmers with regard to their past and the work situations that they construct during the transition. This formalization of transitions *in action* is original in the study of agricultural transitions and in the field of systems and analytical agronomy.

By focusing on the contents of the transition effected by a farmer, we are able to formalize the tools and objects transformed during the transition. The research community studying transitions in agricultural systems has until now concentrated on the *a posteriori* analysis of change. These studies afford access, for example, to a characterization of the extent of changes underway in agricultural systems[14,31] or a characterization of learning trajectories, according to the process (trial and error, experimentation, etc.) taken to construct learning[32].

In our study we propose a conceptualization of the dynamics of agricultural systems in the long term, based on the creativity of farmers' action. Farmers drive change on their farm and manage it partially by mobilizing tools they adapt to the use they can and wish to make of them. As the usage of these tools transforms their activity, farmers re-discover their work, in a sense, which in turn fuels the transition process. Autonomous and self-sufficient mixed crop–dairy farmers give attention to object subject to simplification in agronomy: animal observations to adjust their diet, consideration to the diversity of crops and their link to the soil, the crop rotations, etc. This anthropocentric conceptualization of the dynamics of agricultural systems is original in agronomy. Agronomic conceptualizations leave little room for initiative and improvization by farmers. Agronomists usually represent agricultural systems as technical systems that are stable in the long run[33,34], or systems that function and adapt to natural cycles, on different time steps[35]. More recent formalizations present agricultural systems with reference to the adaptive cycle of Holling[36]: in the long term, agricultural systems cross through a series of stable phases and transition phases[37]. The routes by which these systems adapt and the routes of these farmers are studied in transition phases. These formalizations represent farmers either as beings who react to foreseen situations according to set rules[38], or as actors who depend on fluctuations in their environment[39]. Self-sufficiency regarding inputs is closely tied with the autonomy in decision making of farmers: the skills of the farmer, i.e., self-sufficiency, depends on farmer's ability to make choices autonomously, yet this autonomy, as a value, is also a precondition for the self-sufficiency. It is thus a close co-evolution of the two aspects: farming practices toward low/no external inputs and farmer's observation skills, his knowledge.

In this work, we highlight a panel of key tools that emerge during farmers' transition, along with new objects

on which farmers act during the transition. By construction these tools adhere to the farmers' work situations[40]. Their usage reveals 13 agronomic objects during the transition. We formalize farmers' objects as they use them and not scientific representations of objects. Tools do not respect usual categories of agronomical sciences: crop management is at the same level as work organization, farm equipment, etc. Balance of matter is emblematic of autonomy and self-sufficiency in inputs. Tools such as adjustment of numbers of animals are mobilized to limit the need for fodder when the farm's own production of fodder is insufficient. Autonomy leads to a practice that contradicts prevailing practice, consisting in purchasing fodder, so that the farmer can produce his milk quota. These key tools and objects of transition are potential resources enabling farmers who wish to change to be in concrete situations of transition to autonomy and self-sufficiency in inputs.

The instrumental approach described here contributes to a more global analysis of transition aimed at understanding the initiation of the process of change and at refining the process of instrumentation of tools. This is achieved essentially by analyzing the way in which the use of tools raises questions on the meaning of a farmer's work. In this study, we highlight the change of the objects on which farmers work—change must be seen more broadly as a change of farmer's work in its praxical and axiological dimensions[41].

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Land use and soils disposal: From competition to territorial governance (examples from land use conflicts in the greater Paris region)

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Abstract

Rural, natural and peri-urban areas seem nowadays to become the object of conflicts and tensions because of their multi-functional nature. If these conflicts issue from opposing views about the use of land, they are also determined by the spatial parameters that characterize the pieces of land affected by the projects of land-use transformation, and by the antagonistic relationship between two or several units of action (farmers and local planners, for example). Therefore, there is a need for a new management of rural (and peri-urban) areas, and this is the role of territorial governance, which is the engine of local development, and the tool for better local compromises, involving periods of opposition and streams of negotiation. Territorial governance has to take into account not only negotiations but conflict relations as well and to include both interaction schemes into its framework. Our study assesses the role played by conflicts in land use within a peri-urban context, based on studies on the Greater Paris region, and a case study on the use of agricultural soils on the urban fringe.

Key words: land use, conflicts, governance, urbanization, agricultural soils

Introduction

Many authors nowadays consider that a new paradigm of rural development is emerging in developed countries. In reaction against the agro-industrial and hygienic model of production based on the use of chemical inputs and sanitary control of products, it builds a representation of rural spaces that differs from the exclusive dependence on agriculture or urbanization[1,2]. Additionally significant is the rise of environmental and sustainable-development issues, which are strongly impacting the design of rural activities, especially agricultural activity, as well as influencing public policies through their local implementations, in particular via zoning processes (for example, in Europe Natura 2000, habitat directives, green and blue belts, etc.).

This new paradigm emerges both in the local actors' practices and procedures and in public policies, with rural development seen as a multi-level, multi-actor and multi-faceted process[3]. Multi-level in the diversity of policies and institutions designed to address the issues of rural development, as well as the evolution of the agriculture–society relationship, taking into account the production of public goods, the construction of a new agricultural production model incorporating interactions between agriculture and other activities, and the combining of activities at the enterprise scale in rural areas. Multi-actor because of the interactions between farmers and other rural-area actors and because of the rural development policies designed to bring about new links between the local and the global. Finally, multi-faceted because rural development unfolds into a range of differentiated practices, some of which are emerging and sometimes interconnected (landscape management, nature conservation, agritourism, organic farming, specific agricultural products, short supply chains, etc.) so that elements considered redundant in modernist paradigms acquire new roles in farm-to-farm relationships and in those between farmers and the urban population.

Land use occupies a peculiar position in this new paradigm. One has to notice that soils in rural areas were

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for a long time used predominantly for agriculture and farming, especially when agricultural activity was dominant in rural spaces. However, the great mutations of the 20th century brought huge changes with regards to this ancient organization. The constant decrease in the number of farmers and of the surface of agricultural soils, combined with the emigration of the rural population to urban areas, has been compensated for by a constant increase of non-agricultural activities and land uses for services and industry, or for the extension of natural spaces and forests. Nowadays, the competition between various uses of rural areas is at stake, and agriculture is often a marginal activity in terms of regional or local gross domestic product (GDP) and labor, whereas it often occupies a large portion of local soils. However, its occupation is under fierce competition from other uses like natural areas, tourism resorts, transport, energy and waste infrastructures, and most of all by a constant urban sprawl which becomes predominant in peri-urban areas and urban regions. The variety of land uses is constantly increasing and the competition between various users or local stakeholders raises the question of the use and the future of agricultural soils. At the moment, an increasing share of agricultural land is transferred every year to other non-agricultural uses.

As a consequence, rural, natural and peri-urban areas seem nowadays to become the object of conflicts and tensions because of their multi-functional nature. Indeed, they are considered as a medium for three types of functions that imply opposing uses and as a result lead to competition and oppositions between the local economic and social actors: an economic and productive function (farms, plants, energy settings, roads or railways), a residential and recreational function (the countryside as a living environment for permanent or temporary residents), and a nature conservation function (preservation of biodiversity, of the cultural, natural and geographical heritage). The users of rural land (farmers, craftmen, neo-rural residents, tourists, migrants, residents of urban outskirts, workers, enterprises and public services) often have different and even opposing views concerning what the land should be used for, concerning its development and that of the infrastructure allowing access to it.

These tensions, regardless of their nature, can turn into conflicts[4]. As shown in the literature, the dynamics of land occupation and of land-use transformation are an important source of land-use conflicts. If these conflicts issue from opposing views about the use of land, they are also determined by the spatial parameters that characterize the pieces of land affected by the projects of land-use transformation, whether they are linear infrastructures (a road, for example) or facilities confined to one or more sites (a factory, etc.) (see[5], or[6]) and some specialists[7] suggest that apart from the 'material' dimension of conflicts, which supposes its integration in a spatialized framework, one has to take into account the social and economic point of view, which is that of an antagonistic relationship between two or several units of action (farmers and local planners, for example).

As a matter of fact, there is a need for a new management of rural (and peri-urban) areas. Indeed, social and political rules and the management of land require that the users of rural and peri-urban land consult one another to decide on how to use land, how to manage the environment, the landscape and productions, and how to contribute to the uniqueness of each territory. This is the role of territorial governance, which is the engine of the development of local areas, and the tool for better local compromises, involving periods of opposition and streams of negotiation. As we will demonstrate later, territorial governance has to take into account not only negotiations but conflict relations as well and to include both interaction schemes into its framework.

Indeed, contemporary research tends to focus on consultation and negotiation procedures at local level and seeks to identify the means of promoting cooperation between groups of actors with different interests, and to reveal governance. However, most of these studies fail to thoroughly investigate the question of conflicts and are generally based on *ad hoc* hypotheses or on an idyllic vision in which local relations are all characterized by a desire to communicate and cooperate. We believe that analyzing the relations between land users and defining governance tools necessitate a thorough knowledge of land-use and neighborhood conflicts as they arise in natural, rural and peri-urban areas, of how they emerge and manifest themselves, of their characteristics, of their generic and idiosyncratic nature, as well as the manners in which they are managed and/or solved. However, if the increase in conflictual relations is often alleged, it is seldom proved by the facts. There is no exhaustive survey of the land-use conflicts that arise in these areas. Our study intends to breach this gap, in assessing the role played by conflicts in land use within a peri-urban context, based on studies on the Greater Paris region, and a case study on the use of agricultural soils on the urban fringe.

Competition and Conflicts Over Farmland Uses

The debate about land-use conflicts is regularly justified by concerns about the management of open, agricultural or natural spaces and to the conflicts that take place in these spaces[8–10]. After having highlighted the problematic disappearance of the rural lands that used to surround towns and cities—a disappearance caused by the increasing urbanization of society—some authors showed in the late 1980s how local communities are capable of resisting these phenomena despite the fact that the balance of economic power favors cities. They draw attention to the spatial incompatibilities between the city and agriculture and the oppositions between the 'native' rural communities and the urban society. In this perspective, the

heterogeneity of the processes of resistance indicates that they are strongly dependent on the inherited historical and cultural resources of the rural communities. Since the late 1990s, conflicts in peri-urban areas seem to have again become an object of study for rural experts, particularly because of the increase in social concern about environmental problems[10], but also because of the 'disappearance' of the rural–urban societies opposition and the emergence of a new set of 'rural' qualities which are socially constructed by local actors through new place-based governance mechanisms[11,12].

Thus, as urban studies reveal the role and impacts of land-use conflicts in the place-based governance dynamics[6,13], ruralists and territorial economists multiply local case studies in order to show how new hybrid territorial projects are currently emerging and how they can be interpreted as the beneficial result of crises between local actors[14]. These territories are then considered as experimental models that help design sustainable agricultural systems at the scale of municipal or inter-municipal urban territories. However, the method makes it difficult to adopt more generic conclusions on the relation between conflicts and territorial governance that is only possible by articulating different levels of analysis. The quantitative analysis that would usefully complement this case study approach has been driven today only by urbanists and planning experts, whose works have highlighted the spatial link between land-use conflicts and socioeconomic level of local communities at the metropolitan area scale.

Many papers have examined the conflicts and analyzed their development and local characteristics. Most authors have found that the diversity of tensions related to the many uses of land makes them, on the whole, difficult to observe and survey; as they are not always expressed, trying to make an inventory of them would be unrealistic. Focusing exclusively on actual protests[15] would drastically narrow the field of observation, at the risk of missing out on interesting information. An intermediate option—certainly the most open and operational—is to identify conflict through the observation of the act of opposition of at least one of the protagonists; it is this act, limited in time and space, that indicates a crystallization of the tensions.

In order to define the conflict as an object of study, we used a conceptual framework based on criteria that have enabled us to differentiate between the situations of tension, sometimes referred to as 'latent' conflict, from situations of open conflict. Though the antagonisms between the different uses of space generate many types of tension between the actors, the analyses based on Game Theory use the notion of credible engagement or commitment to distinguish conflict from tension. Commitment manifests itself in more or less institutional forms (verbal opposition, written signs, registered letters and administrative proceedings) or in more or less radical ways (assault, signs forbidding access and fences). In order to be credible, this engagement necessitates a monetary or more hedonic investment. It is a constraint that the actors impose on themselves and that determines their future positioning. We define as conflict an opposition between actors with antagonistic goals, an opposition that leads to the credible engagement of at least one of the parties.

We define as conflict over farmland uses all of the land-use conflicts that fulfill at least one of the following three conditions: the contested land use is related to farming or agro-industrial sector activities; the contested land use jeopardizes the efficiency of the current farming run in the area; the agricultural legal nature of the land is threatened by the contested use.

Agricultural and Land-use Conflicts in the Greater Paris Region: Nature and Diversity of the Contested Facilities

In order to assess the importance of conflicts we built a database over several situations of conflicts over various French rural and peri-urban areas (see annex)[16]. We extracted data about land-use conflicts in the Greater Paris area from the Conflict© database, based on studies on daily press articles published in *Le Parisien* (Regional daily newspaper). The choice of the Greater Paris region is motivated by the competition between various land uses and by the high number of local stakeholders, following different and often opposite goals.

A first inventory of all of the land-use conflicts reported in 2005 (182 in total), indicated that agriculture is seldom the object of conflict and that the actors of the agricultural industry are rarely involved in conflicts. However, 30% of the latter are related to the non-agricultural use of open pieces of land identified as agricultural (cultivated, fallow or meant for farming). Furthermore, this first inventory highlighted, first that local elected representatives and associations are involved in the majority of the conflicts (70%), and secondly that a large percentage of the conflicts are related not only to uses but also, more specifically, to land-use regulation (40% of the conflicts).

We then extended the inventory of agriculture-related conflicts to cover two additional years (2003 and 2004), which enabled us to build a database referencing 90 conflicts of various scopes and intensities, related to the use of agri-urban resources. Compiled in the form of a relational database, the information found in the newspaper articles, once encoded, enabled us to locate the Municipalities in which one or several conflicts occurred between 2003 and 2005.

Using these data, we are able to describe the diversity of the contested objects and the nature of the antagonisms they generate and which cause the actors' reaction. A first quantitative synthesis of the information found in the press concerning actors engaged in conflicts shows that it is less the reaction of the actual users of land (professionals, individuals) than the actions of their representatives (elected representatives, associations and

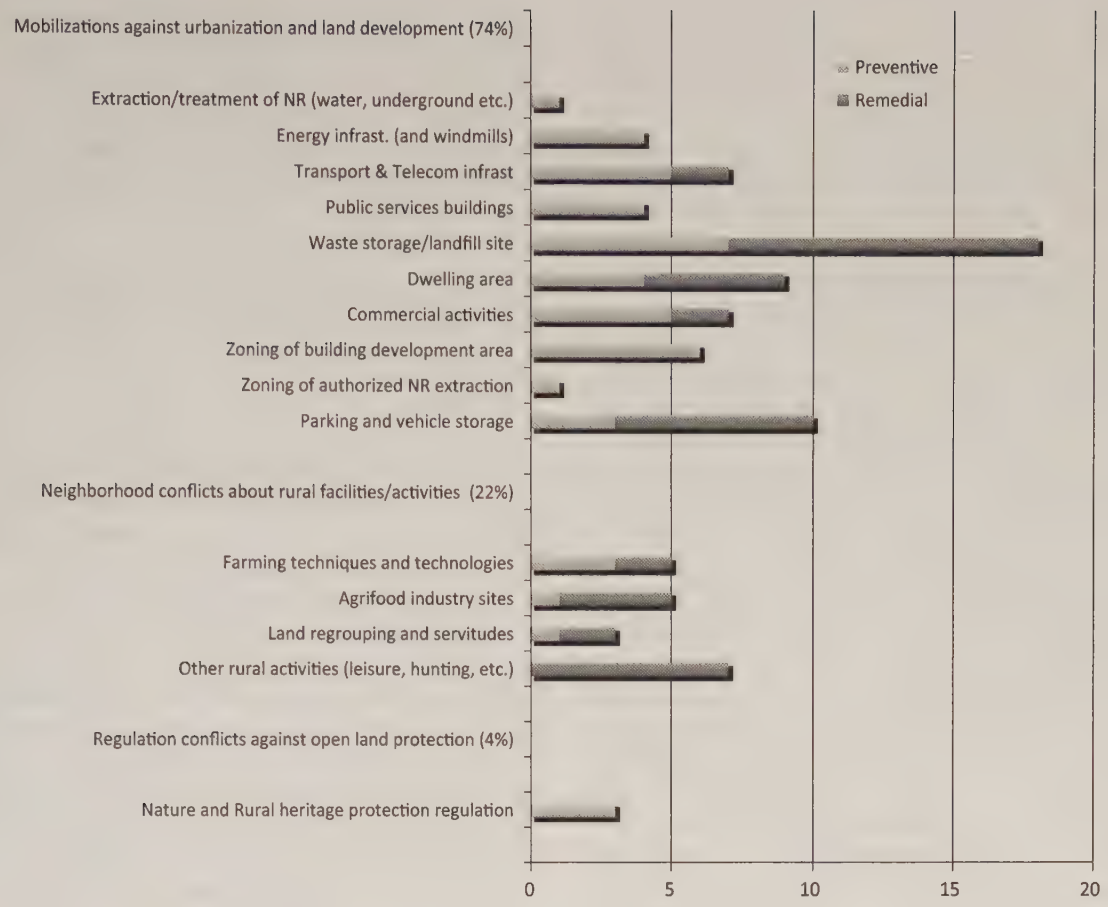

Figure 1. Categories and detailed objects of land-use conflicts found in the paper *Le Parisien* during the 2003–2005 period.

representatives of the public authorities) that are reported in newspapers. Among these representatives, municipally elected officials and local or generalist associations are those that initiate most of the actions covered by the press, whereas the representatives of State authorities, municipal elected officials and professional users are the group of actors that are the most contested. Moreover, the majority of conflicts (57.7%) occur in an attempt to prevent the creation or development of objects or facilities considered to be associated with environmental constraints (the other conflicts are remedial). They are triggered by people who seek to minimize or eliminate a nuisance they are already experiencing.

In order to go beyond this first set of generic results, we grouped the various patterns of oppositions into three main categories. It allows us to draw a qualitative and quantitative picture of the variety of farmland-use conflicts in the peri-urban area.

Collective mobilization against urban development and its negative impacts: The dominant feature

The most frequent conflicts are those opposing local actors about the negative impacts of urban activities and urbanization proximity upon the rural resources used by farming (soil, water and atmosphere). The initial opponents are mostly local residents. They protest against the nuisances generated by the city, which are considered as a threat to the rural quality of their life environment. Farmland and agricultural spaces are thus mentioned during debates to qualify what is preferred compared to the rejected urban developments or activities.

An illustrative example of this kind of conflict would be that of Pierrelaye. A struggle against illegal landfills is based on the public recognition of the productive value of the farmlands concerned by local government. Even if the soil here is highly polluted by decades of sewage spreading and market gardening is forbidden (even corn cropping had to be restricted because of pest control regulation linked to the proximity of international airport Charles de Gaulle), public regulation of the fields and lanes is supported by the local budget under the objective of protecting the productive spaces and resources of local farmers.

From a quantitative perspective, this category is the most important in our collection. It groups 74% of the cases. Non-governmental organizations (NGOs) and civic associations are frequently involved, which could explain why media publicity and administrative litigations are the dominant means of expressing the conflict. Among the many sources of dissatisfaction reported (Fig. 1), the

most frequent are those linked to urban waste and sewage management, before those linked to illegal parking, dwelling and commercial areas or transport infrastructures (mainly road construction).

Among the conflicts triggered by groups opposing the urbanization of agricultural land, three scales of conflicts can be distinguished that correspond to different categories of contested objects and uses. They are the conflicts related to regional development, those related to the management of municipal land, and those related to the consequences of urbanization.

- In the first case, the conflictual interactions develop at the scale of a sub-region, through alliances between elected officials and associations who oppose representatives of the public authorities accused of supporting private developers or as managers of regional development and planning.
- In the case of conflicts related to the management of municipal land, the conflictual interactions only involve members of the municipality. The municipal council plays an important role here.
- Finally, the conflicts triggered by actors who protest against the nuisance and constraints generated by agricultural activities develop mostly at the scale of the municipal territories and their neighboring areas. They involve local environmental associations and municipal officials who oppose the professional representatives of the agricultural or agribusiness sector.

Neighborhood conflicts against farming nuisance, not so numerous

As suggested by the previous results, and contrary to the opinion of many experts, neighborhood disagreements are not the main source of conflict in peri-urban areas. This category still groups 22% of our collection and shows an interesting variety of patterns.

If some articles record the case of neighbors specifically contesting cropping or livestock farming activities, another frequent case is the one against agri-food storage and logistic facilities developments and two cases concern the polemics about agricultural land development (drilling and land regrouping) and their environmental consequences upon the scarcity and quality of natural resources (here water and groves).

In terms of social interactions, even if personal interests are the main motivation of the contestants, inter-individual oppositions are not the norm in this category. Individuals often regroup within collective organizations in order to reach their elected representatives' attention and initiate an institutional regulation process or, also, to engage in litigation.

Finally, neighborhood conflicts can also be categorized not by farming activities but by rural dwellers' activities, such as motorized leisure or hunting societies. In this case, farmers often contest the development of private hunting societies (which tend to flourish around the Parisian agglomeration in order to satisfy an increasing demand from a section of the rich population and workers, but which fail to regulate the wild boar livestock they introduce). Of course, by definition, the press is only showing us the visible patterns of this category of conflicts, which we can imagine as being proportionally more important in reality.

Private landowners resisting open land regulations, the beginning of collective action

The last category that we could identify is almost anecdotal in terms of the number of cases but nevertheless represents a significantly original pattern that we could find more often in other sources, such as administrative litigations for example[17]. They involve engagement between private landowners and public administration about the legitimacy of open land regulation.

The press records here the original situation where the public landscape and natural resources protection regulation is being contested in court by landowners' collective organizations and farmers' elected representatives. The latter argue that open land protection regulation can impact farming economy by adding developmental constraints, such as architectural and land development restrictions or arboriculture constraints (in the case of forest protection regulation). This is, for example, the case of the administrative litigation engaged in against the rural landscape heritage protection perimeter of the Plaine de Jouars (Yvelines).

Complex and intricate conflict behaviors

To conclude with the conflicts, we have established that the information provided by the press indicates that the uses of agri-urban resources are regulated through social processes, and more particularly through protests against the development of regulations or infrastructures serving urban and non-agricultural activities. A number of these conflicts are related to the implementation of urban waste management facilities and to certain unplanned temporary uses of open spaces. Indeed, the urban consumption of agricultural land is regulated, and the degradation of the water and atmospheric resources circulating between different peri-urban territories is controlled through protest against these uses.

Other articles in our collection reveal, however, that other types of conflicts also play a part in this regulation; these conflicts involve protests against the impact of certain agricultural facilities or practices on the resources destined for urban consumption. The nature of the groups of actors initiating these processes of regulation is determined, on the one hand, by their ability to show the links between the resources under threat and the contested facilities or practices, and on the other, their ability to approach hierarchically or influence networks so as to be able to take action at the appropriate governance level

(i.e., territorial, governmental or economic authorities). We have also shown that all of these conditions were met, in the case of preventive conflicts, within upper and middle class residential rural municipalities, and, in the case of remedial conflicts, within middle class residential rural municipalities as well as in the newly attractive rural villages. One has to wonder whether these changes and oppositions can be handled by the new CAP in Europe, and most of all by the new smart development EU policy, which claims sustainable and inclusive development for regions and areas.

Territorial Governance at the Heart of the Competition between Land-use Competition

We have seen that various conflicts arise around competition for land use or, most of all, for agricultural land. We will demonstrate that these conflicts are part of the territorial governance process, and that they occupy a particular position in this complex arrangement. They are ways to improve the decision around the development of the territories and the choice of uses for agricultural soils.

The notion of governance is rather blurred and ambiguous; Pasquier et al.[18] define it as 'a set of rules and styles making possible the conduct of a public action' in a context where society is becoming more and more differentiated (and autonomous) and where there are more and more interested parties, or the notion is sometimes presented as a government of compromise or as a process of multi-level and multi-polar coordination in a strongly asymmetric context where there are many decision centers.

Following institutional innovations brought about by decentralization and contractualization in many countries, the participants have been led to try out new forms of public action and involvement in decision making, passing from a pyramidal or hierarchical organization, founded on the public institutions, to a network-type organisation[19,20] that combines public–private partnerships[21] and involves a highly varied group of players[22] and multiple territorial levels[23].

Yet, the government must continue. The tools of governance are therefore aimed at easing the participation of more and more varied public of parties or of those with interests (public representatives versus private lobbies, political agents versus members of associations) in decision processes that are more and more fragmented and dispersed and at the same time less and less certain. This is the rupture of the governmental approach to public affairs by hermetic administrative and political devices, and the upsurge of questions of local democracy in the management procedures of people and organizations.

Governance involves the participation of players with heterogeneous preferences in the decision process, people from different groups each with their particular incentives. It becomes a focal point, focusing the numerous contributions in coordination, interaction, collective action, empowerment and learning—with a special emphasis on participation and consultation. In some human sciences—institutional economy, political science, sociology and management—discussions may be about a specific object, but much interdisciplinary work revolves around a few key themes: expertise and public action, the general interest, participative governance, property rights, community governance, development, public policies, governance *vis-à-vis* the issue of proximity, voluntary schemes, equal access to resources, as borne out by the terms of world, European, urban or environmental governance, etc.

Thinking in terms of territorial governance refers to concrete objectives in terms of local and rural development[24]:

- to favor the setting up of territorial development projects;
- to contribute to the design of wide consultation schemes;
- to facilitate the coordination of heterogeneous groups of players;
- to limit the spatial exit of people with certain profiles;
- to avoid sterile confrontations;
- to decide on development pathways.

Through this stance there also appears a renewal of the methods whereby a representation or a common project is constructed. It shakes up the schemes to be set up and calls for a reinforcement of the processes of local democracy or deliberative democracy.

Territorial Governance and Land-use Conflicts

Our research on the conflicts in rural and peri-urban areas shows that they are essential in the land development processes or in the management of various local functions. Land-use conflicts are a form of expression of opposition to decisions that leave part of the local population unsatisfied[4]. Some local innovations provoke resistance which can give rise to conflicts. Major changes, which involve reconfiguration of the use of space (introduction of transport or waste treatment infrastructures, new local urbanism plans, and territorial or environmental zones) generate conflicts whose spatial and social extent can become very considerable.

Conflicts are thus one way of entering into the discussions on the stakes and ways of territorial development, and of affecting the decisions by involvement in processes from which one had been excluded[25]. This is the reason why they bear either on the decisions that have been taken on development (arbitrated negotiation) or on the composition and representativeness of the bodies in charge of the decision (arbitration). The conflict is also

an integral part of the process of deliberation at the local level, allowing an expression of local democracy and the re-integration of players who were forgotten or left aside in a previous phase of project design.

Territorial governance is not limited to an idyllic vision of economic and social relations, i.e., to forms of cooperation and common constructions[26]. It is also about interaction between forces promoting cooperation and other forces promoting conflict. The processes of territorial development and their progress over time do not in any case resemble a long and tranquil river. They are made of phases of negotiation, collaboration or appeasement, and of much rougher periods when certain groups or categories of players clash, sometimes violently, in defining the steps to be followed and the options to be adopted. The process of the governance of territories thus has two complementary sides, the reciprocal importance of which varies with periods and situations. It feeds on opposing tendencies[27], whose reconciliation leads to a definition of path development.

Our research shows that this dimension is also key in processes of territorial management, regional development or the governance of various local activities. It appears in the form of litigation, media events or violent protests. In most cases, land-use conflicts are not blind oppositions or purely egoistical in origin but constitute a way of initiating discussions on the issues and paths of territorial development and of influencing decisions by participating in processes underway from which one had been excluded[25].

Land-use conflicts thus constitute one form of resistance and expression of opposition to decisions that leave part of the local population unsatisfied[4,14]. Some local innovations, whether technical or organizational in nature, give rise to resistance which can turn into conflict. Major changes requiring reconfiguration of the use of space (creation of transport, energy or waste-processing infrastructure, new urban master plans, territorial or environmental zoning, etc.) generate conflicts whose spatial and social extent can quickly grow. Conflicts are signals of social, technological and economic changes and indicators of novelty and innovations. They demonstrate the opposition aroused by the latter, lead to discussions on their implementations and their possible (non-) acceptability as well as on the adoption of governance procedures, and their transformation under the influence of the dynamics of change. All of the changes encounter opposition or resistance of varying relevance and justification. However, it would be simplistic to see this resistance as a systemic sign of reactionary opposition to change because, in a number of cases, they are more a reflection of differences over the direction taken by the new initiatives that are being imposed on the public than of a stubborn desire to maintain the status quo. During these phases of conflict, social and interest groups tend to reconstitute themselves and may even undergo technical or legal changes. Once a conflict ends, it leaves behind new local agreements, new modes of governance, new configurations of discussion forums as well as new technical procedures (changes in direction, various adjustments, changes in urban planning documents, etc.), all arrived at during the negotiations. Harbingers of territorial innovation, conflicts are thus both the result as well as the cause of territorial changes, as shown below, with the case study of the Plateau Briard, located on the border of the Paris agglomeration.

Conflicts and Territorial Governance: The Case of the Plateau Briard

In order to assess the development of conflicts related to (mostly) agricultural land uses in the greater Paris region and to reveal the role they play in the process of territorial government of local areas, we will examine the example of the three 'farming domains' located 20 km from the center of Paris, in the Plateau Briard district (Fig. 2). This area is composed of six municipalities which share a common concern about the preservation of farmland in the context of great urbanization pressure due to the direct proximity of the Parisian conurbation. Its demographic growth rate was still high in 1999 (+4.3% between 1990 and 1999, compared to +1% for the Val-de-Marne département) due to the qualitative living environment and the quantity of building lands available. On the 3169 ha of the district, 23% are farmlands (747 ha) divided between the 45 local farms of four municipalities: Varennes-Jarcy, Santeny, Mandres-les-Roses and Périgny-sur-Yerres, the two last municipalities being already totally urbanized. In Santeny and Varennes-Jarcy, the majority of the farmlands are used for grain production and some horse-breeding farms.

In the municipalities of Mandres-les-Roses and Périgny-sur-Yerres, horticulturists and market gardeners are living and producing within the perimeter of three original housing estates dedicated to farming activities: the Roseval, Rosebrie, and Saint-Leu domains. Since 2001, they have been integrated in a local action program implemented by six municipal councils which aims to preserve the last farmlands of the Plateau Briard district. Even though they were created at the same period of time, the domains show significant differences in terms of estate planning and architecture and of collective functions of open land.

The two domains of Mandres-les-Roses (Roseval, 29 ha, and Rosebrie, 65 ha) are dedicated to horticulture. The settlement design follows the plans traditionally used by the administrative agents in charge of the project at the time (Agents of the Direction Départementale de l'Agriculture (central state farm development agency) and Société d'Aménagement Foncier et d'Etablissement Rural (SAFER: public institution in charge of public rural settlement operations).). It looks like a classical housing estate, each farmer's house being regularly distributed along the two sides of a circular lane equipped with public

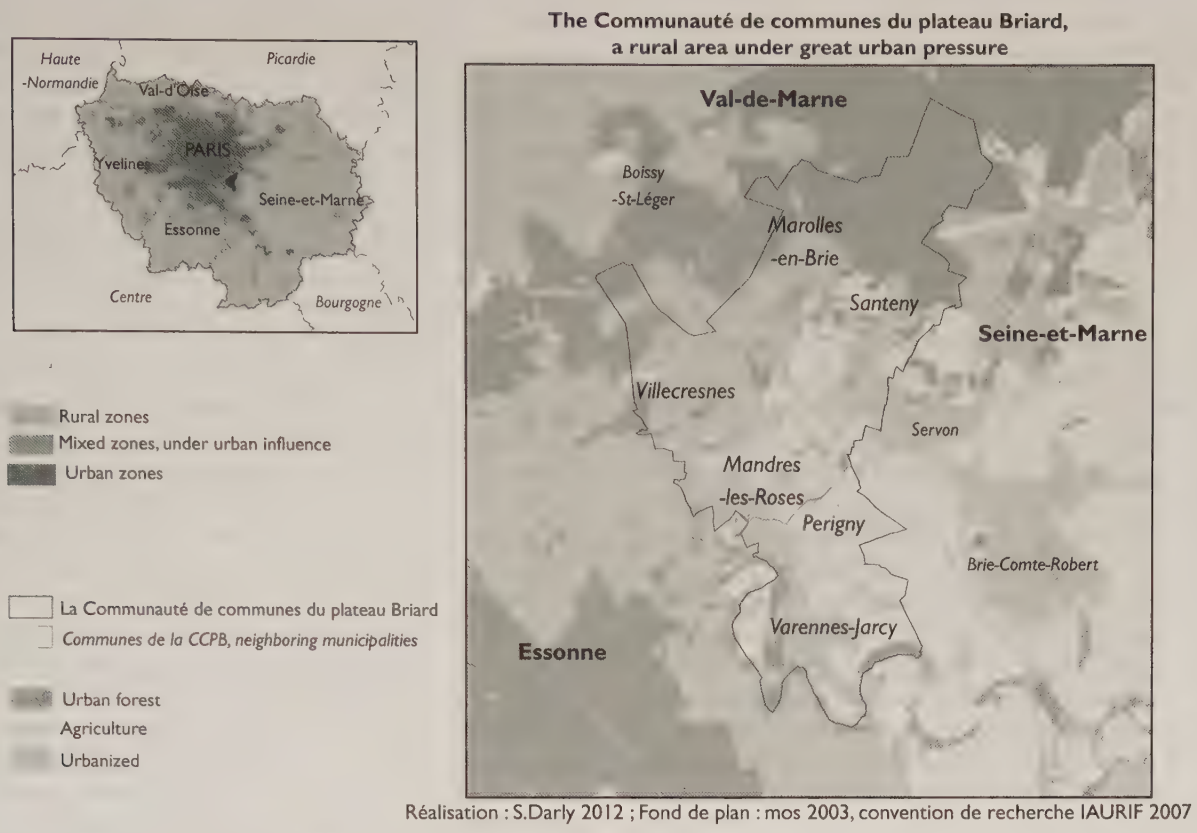

Figure 2. The Plateau Briard, in the Greater Paris Region.

lighting and sidewalks, except that the plots have been specifically sized (2000 m^2 each) and arranged (with fences) for the growing and production of fresh flowers in greenhouses, which were to be exported on the international market. This spatial configuration leaves today very few possibilities of developing other farming activities. By comparison, the Saint-Leu Domain, 86 ha, looks very different. The land is mainly used for market gardening (no greenhouses), also sold on the international market. The plots are bigger (2–3 ha) and with no fence closing them. There are no 'streets' but farming lanes with no sidewalks but green hedges, and a public 'House of the Nature' welcomes visitors at the entrance of the estate.

We interviewed several elected representatives and farmers who took part in the decision making of the domains' creation and, later, of the Plateau Briard district. This field survey gave us empirical material to illustrate how conflict interactions are at the core of a local dynamic for the preservation of specific interests linked to the protection of open farmlands and how they participate to the differentiation of the city countryside.

Making of the domains: tensions arise

The production of roses was developed at Mandres-les-Roses in the 18th century. At that time, they were transported directly by train to the market place of La Bastille in Paris. This activity almost ended with the rapid growth of the capital in the 1960s when the high rate of house and road building consumed all of the farmland and greenhouses owned by rose producers. The rose production tradition survived on other plots in the municipality and only thanks to state intervention. In 1965, the Caisse des Dépôts et Consignations (CDC) bought one vast farmland of a local cereal farming family. By the beginning of 1970, state representatives intervened to stop the urbanization process of the area and managed to locate on the plot, through SAFER mediation, several horticulturists who had been expelled from newly created new towns. In the 1980s, when the state encouraged the adoption of local planning documents, the plots had been integrated under a 'C' zone (C meaning that the land located in the zone can only be used for farming). This was seen as a minor detail at that time but became, as we will see below, a major object of tension 10 years later.

The story of Saint-Leu is quite different. If the resistance to urbanization is also at the basis of the domain project, it has been carried on mostly by local actors and not by central state representatives. During a municipal council meeting in 1967, the mayor asked the council to allow the notification of a public housing project that was planned on a plot sold 2 years earlier to the CDC (along with the plots of Mandres-les-Roses). The council rejected the request, arguing against the high cost of the operation and, most of all, the loss of valuable farmlands in a locality that included several market

gardeners in search of land. A few days after the vote, the mayor resigned and a new council was elected, led by a non-farmer resident and several market gardeners. Very soon, the newly elected team had to face a great number of similar housing projects and searched for public regulation tools that would help them to regulate the conversion of the remaining farmlands. In cooperation with the central state services, they experimented in 1974 with local planning documents (Plan d'Occupation du Sol), using for the first time 'C' zoning in order to forbid building on farmlands. The C zoning sent a strong message to the landowners (one cereal farmer and several non-farmer owners). They gradually agreed to sell their plots at a lower price than the housing land price (but still higher than the current farm land price) so that a regrouping of lands could be performed.

In the mid-1970s, a rise of energy costs and strong international competition in the fresh flower market began to reveal the weakness of the greenhouse and rose monoculture systems implemented at Mandres-les-Roses. As the classical farm housing estate projects were designed for greenhouses and horticulture, the Périgny farm workers who were candidates to buy farmland were planning on developing market gardening. However, plain field market gardening requires bigger plots and therefore increases the total cost of the operation. To compensate for this fact, market gardeners thought about lowering the cost of the domain settlements (road, lighting and sidewalks). They failed at convincing SAFER to design a new form of farm housing estate. Hence, the group of market gardeners, helped by the municipality, created its own local land settlement agency through which they were able to divide and equip the plots as they planned. In the process, the non-farmer members of the municipal council negotiated that part of the domain would be dedicated to collective uses through what was called at the time an 'agro-touristic complex': hedges were designed for biodiversity protection, pedestrian lanes were include in the plans, and a plot was set aside for a communal 'House of the Nature'.

The life of the domains in the 1990s: from tensions to conflicts

In the 1990s, tensions grew to conflicts in the Plateau Briard area. During the early 1990s, horticulture and market gardening were strongly exposed to international competition, whereas the two sectors stayed outside of the European common market policy. The interest of the landowners in farming activity was therefore strongly decreasing: the lack of private investments, the closing of the weakest farms, and the high costs of greenhouse destruction explain the multiplication of fallow lands inside the domains. The period seemed to have favored the expression of neighborhood tensions between residents and farmers: horticulturists from Rosebrie complained about the lack of public maintenance of their lane, while requests were addressed to the municipal council about the mud tracks left by the tractors on the roads. In Périgny, the 'Home of the Nature' was no longer used, the pedestrian lanes began to deteriorate and the market gardeners intended to cut the hedges whose roots plugged the drains. However, if the tensions were numerous, a few of them were expressed through open conflicts. This period appears as a transition, through which the physical and economic environment evolved slowly as the tensions were regulated by the key elected representatives that created the domains.

From the middle of the 1990s, the acceleration of retirement departures in the domains and the renewal of the members of the elected council set the grounds for a period of further conflict. In Mandres-les-Roses, fallow lands were more and more numerous and tensions between horticulturist landowners and the members of the municipal council resulted in the crisis that surrounded the rewriting of the local planning documents in 1994. C zoning of the two domains was indeed confirmed in the new project, whereas the landowners counted on the end of the zoning to sell and stop farming activities. Strong oppositions were expressed, and one council meeting was interrupted by the violent intrusion of farmers.

In Périgny-sur-Yerres, the fallow lands problem is nonexistent and the market gardening business is more resistant to global economy competition. Still, several market gardeners facing marketing difficulties would prefer to convert farmland if the zoning becomes less restrictive. To secure the protection of open lands, the municipal council, with the regional council of Ile-de-France, established in 2003, a PRIF (regional perimeter for public intervention over farmland property) over the domain and other locations. The strong tensions remaining between pro- and anti-domains in Mandres-les-Roses made it impossible for the municipal council to vote for the extension of the PRIF on its territory. In 2007 (when the last interviews were held), land property regulation was still highly conflictual, even in Périgny-sur-Yerres. Administrative agents are openly criticized during public meetings and the information notices installed along the pedestrian lane are frequently damaged.

From municipal conflicts to inter-communal governance

Since the end of the 1990s, local stakeholders have tried to set up a new period of cooperation, in order to improve local governance. The elected representatives of Mandres-les-Roses tried to support the local farming development program in order to lower the tensions due to farmland property rights regulation. During this period, the central state was trying to reform the collectivities' organization by gathering municipalities into intercommunalities (inter-municipalities). The Plateau Briard district is one of these new intercommunalities, formed by the gathering of six municipalities in 2002, and was designated to

manage the farm development project (named 'agri-urban' program) that the institutional partners agreed to finance.

The geography of the district reveals the tensions between the municipalities that cooperate to protect farmlands and the urban agglomerations that surround them: Community of agglomeration (CA) of la Plaine Centrale du Val de Marne around Créteil, CA of Haut Val de Marne around Boissy St Léger, CA of Val d'Yerres around Yerres, and Syndicat d'Agglomération Nouvelle (SAN) of Sénart. The identity of the new district is therefore based on a common objective of resistance to urbanization rather than on a common vision of farmland development. This incidental association must not mask the differences between Mandres and Périgny that are still structuring the public action for farmland preservation.

Even if the risk of housing development is higher in Mandres-les-Roses (due to a weaker farming sector), the municipal council, as we said before, rejected the PRIF in 2003, and, several year later, refused the 'agri-urban' action program of the Plateau Briard which includes the project ZAP (Zone d'Agriculture Protégée) proposed by the council of Périgny. For the elected representatives of Périgny and Mandres, the Plateau Briard district is on the one hand a common platform used to resist urbanization, and on the other hand, a new arena of conflict between two very different municipal 'agri-urban' legacies.

To sum up, the limit revealed by the early stages of the Plateau Briard conflict chronology was the 'top-down' government paradigm that most central states services were following in the 1970s and their inefficiency with regard to agricultural land planning. Rigidity not only in the urban but also in the rural development models adopted by the CDC or SAFER have been condemned throughout conflicts that led to the early experiment of innovative local planning governance. The multiplication of conflicts between the municipal council and the landowners highlights the need to re-evaluate public and private decisions as the interests of the landowners change with time, and also reveals the innovative role of the conflicts, which gave birth to new solutions in terms of territorial governance, such as the so-called agri-urban programs.

Conclusions

Territorial governance processes are today undergoing intense upheaval and are subject to intense periods of discussions and conflictual opposition. These latter shape the phases of territorial innovation and thus change the directions of development and growth in rural or urban territories. Such governance mechanisms and their associated conflicts can be viewed as laboratories of change because they accompany, and sometimes anticipate, the changes underway in the territories by giving them shape, by helping maintain a dialogue and expressions of opposition, and by preventing violent confrontations or failures of development due to sluggishness or expatriation. Therefore, these changes in land-use occupations and the subsequent oppositions they gave birth to are embodied in the opposing and twin forms of conflict and consultation which constitute the modes of expression and the vehicles of transmission of on-going innovations at the territorial level.

The Plateau Briard case study highlights how conflicts reveal and regulate the limits of farmland governance, and give birth to territorial innovation, in terms of local arrangements or institutional set-ups. From a more general perspective, it shows that the conflicts give us an insight into the interests defended by each actor involved in the farmland governance and on the power relations associated with innovative collective projects that emerge from them. Cooperation and conflict relations are the two faces of territorial governance relations, and interactions and tensions between the local actors are constituents of the modalities of territorial governance of various land-use projects and expectations.

As a matter of fact, land-use configurations strongly depend on the balance between conflicts and negotiations in the territories. If negotiation is successful and local compromises are reached, then the actors are likely to develop relations of cooperation, and even of trust and synergy. If, on the contrary, the actors oppose one another, conflicts emerge and condition the relations between the local actors. Recourse to territorial governance is all the more necessary as the conflicts intensify. Indeed, few are the territories that can go through long periods of time without conflict, if only because conflicts serve to reveal social, institutional or technological innovation in the territories.

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Annex—Observing conflicts: Sources and methods

In order to better understand and analyze the conflicts that have emerged in rural and peri-urban areas we have initiated a program of research on neighborhood and land-use conflicts. This program is based on an empirical and deductive approach and aims to analyze how conflicts emerging on the French territory develop and how attempts to solve them are undertaken. It has proved not only the importance of land use conflicts over agricultural soils, but also their core role in the process of territorial governance.

Analyzing conflict events necessitates data on actual conflicts so as to be able to empirically measure the opposition phenomena, the modes of expression of conflicts, their causes, origins or the solutions proposed to end them. However, the data related to conflicts is scarce or incomplete for two main reasons: the little interest taken until the year 2000, in this question, as well as the complexity of the conflicts—conflicts which find expression in various modes (tribunals, media coverage, and demonstrations)—make it difficult to represent conflicts and require the input of various disciplines for their definition. The analysis of conflicts can only be conducted on the basis of information collected from different sources.

In France, as in other countries, there is no system of statistics on conflicts related to the use of land and territorialized resources (landscapes, etc.). A group of INRA, CNRS, and university researchers in different fields (economics, sociology, geography, and social-psychology), among whom the authors of this article, have developed—with public financial support—a database on land-use conflicts that occur in the French territories. It is original and responds to a desire to make an exhaustive inventory of the conflicts, and is fed by three different types of sources: the Daily Regional Press, civil disputes, and qualitative surveys. The data from the first two sources are made compatible by a common nomenclature and common variables, developed collectively and which are combined to data related to the socio-economic context. The scale used is the commune (or town/ municipality).

- The definition of land use and neighboring conflict rests on three elements:
  The distinction between conflicts and tensions. In relation to tension, a conflict implies the crossing of a qualitative threshold, corresponding to the engagement of the parties in a conflictual relation and aims to give credibility to their positions. Engagement implies a cost which may be financial or hedonistic—and which can take different forms: Actions at law, bringing the matter to the attention of the public authorities or of the civil service representatives; Mediatization (bringing the matter to the attention of the media, press, radio, and television); Assault or verbal confrontation; the destruction of property or infrastructures, Putting up visible signals (signs forbidding access, fences and gates, etc.).
- The spatial dimension of land use conflict. Land use conflicts concern a physical good; they arise between neighbors, around the use of localized support material, or immaterial goods; They have an institutional dimension in that they are determined by both the actions of local and supra local authorities and by the rules they introduce.
- Materiality. The conflicts we are interested in are related to a materiality of the actions that have taken place or are anticipated. The oppositions between people or groups of people refer to concrete objects, to technical acts that are taking place or will take place and imply concrete actions.
- Development and infrastructure projects have been identified as the material objects triggering conflict: installation of a mobile telephone relay station, construction of a road, etc. This material object can be formulated in legal terms in a different register, for example, when the petitioners protest against a decision to modify a local urban development plan the ultimate purpose of which is to allow for the construction of an infrastructure. The documentary base enables us to identify the material object of each conflict and the juridical field of the motion.

The overall structure of the Conflicts© database is based on three main data tables:

- A table containing the variables relative to the geographical locations of the conflicts (in relation to a municipality, a community of municipalities, or a *département*)
- A table indicating the variables describing the conflicts *per se*, that is, the cross sectional categories which are identical whatever the source of the survey, and the categories relative to a context of observation (The legal categories defining, for example, the nature of a request made to a jurisdiction.);
- And finally a table providing information about the profile of the actors involved.

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Landscape characterization of integrated crop–livestock systems in three case studies of the tropics

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Abstract

Integrated crop–livestock systems in the tropical region are diverse and not well characterized. To better understand the conditions and potential of these systems, we characterized the spatial and social arrangement of integrated systems within a landscape context. Integrated systems are defined by biomass and nutrient flows, linking crop, livestock and human components of agriculture. The landscape is defined within a spatial framework of these flows. To understand the diversity of integrated systems in the tropics, we characterized three case study areas: Southern Mali, Brazilian *Cerrados* and Amazon frontier. Methodology was based on historical and descriptive approaches of these cases, mobilizing interdisciplinary knowledge of a large research team. This provided a retrospective view to discuss four key points about the future of integrated systems in the tropics: (i) importance of landscape structure for conception and adaptation of the integrated systems; (ii) key role of local institutions in managing such integrated systems; (iii) trade-offs between external and internal resources; and (iv) role of nitrogen to improve system efficiency. This paper concludes with the relevance of social sciences in the further development of integrated systems.

Key words: integrated crop–livestock systems, landscape characteristics, multi-scale analysis, biomass flows, sustainability, tropical region

Introduction

Diversity of agrarian dynamics in tropical areas complicates the analysis of integrated systems potentials

Integrated crop–livestock systems, or crop–livestock–forestry systems, have been seen as one of the main alternative routes to reach millennium development goals for agriculture and food production. Integrated systems may foster an increase in animal and crop production, as well as potentially greater expression of ecosystem services and protection of environmental quality to meet a growing demand for food during the next few decades[1,2]. However, the contribution of integrated systems is still considered minor on a global scale. There is a need for greater diffusion throughout the main agricultural regions. The tropical region is considered strategic in this matter[3], as it holds large portions of arable land. The region has a large potential in terms of land production and workforce, as well as an abundance of natural resources, such as solar energy, water, soil and biodiversity. However, agricultural systems in the tropics are very diverse[4]. Studies are needed to analyze the conditions and evaluate the adaptation and expansion potential of integrated systems[5]. Agricultural diversity not only creates obstacles when trying to understand and compare systems, but also when seeking pertinent local adaptation options. Common ground is needed to identify windows of opportunity and pertinent lines of analysis.

With a view toward expansion of integrated crop–livestock–forestry systems, our focus was on understanding agricultural diversity to identify common threads among spatial arrangements in different tropical settings. We asked the following research question: what are the contributions of the spatial dimension in understanding

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Table 1. Specifics of integrated systems in three case study areas.

	Soudanian Mali	Brazilian *Cerrados*	Amazon frontier
Area studied	Dentiola, village in the Koutiala District	*Rio Verde de Goiás* Microregion	Municipality of *Paragominas*
Integrating spatial scale	Village	Region	Farm
Landscape delimitation	Ecological definition: toposequence	Economical definition: raw material basin of a company	Land tenure definition: individual land property
Farming system	Diversified crop, livestock, forestry	Specialized, crops or livestock	Specialized livestock, beginning crop and forestry
Farm spatial organization	Small fields, scattered	Large fields, grouped	Large fields, grouped
Main integration flow paths	Manure and forage	Animal feed, forage, manure, chemical soils fertilizers	Chemical soil fertilizers, water, forage

the diversity of integrated systems in the tropics for identifying limitations and prospective development?

Integrated crop–livestock systems in different rural landscapes and social conditions

Our aim was to demonstrate how spatial and multi-scale analysis might enhance the concept of integrated crop–livestock–forestry systems, and its adaptation to various other agricultural situations in the tropics. Adapting to variability in the tropics is necessary, because of the inherent causes of variation that force farmers to recognize this situation. Our approach was focused on spatial models and not technical models.

We targeted flow paths among crop, livestock and forestry components in integrated systems[6]. In integrated systems, energy, water and nutrition flows are intended to benefit crop, livestock and forestry components. Tree species may, for instance, improve the water cycle for the benefit of crops or livestock, by limiting evaporation and creating shade. Animal manure may enrich the soil to benefit cultivated crops[7]. Herd management practices, crop rotations and spatial arrangements of farm operations can all help to improve cycling and flows among components.

The spatial dimension is key to the concept of material cycles and energy flows and management of integrated systems. Flow paths connect a point of origin to an end, materializing a spatial distance. In some systems, this distance is only vertical, e.g., flows between a tree crown and the soil. In other cases, the spatial distance is null, i.e., nutrient flows may be seasonal, resulting in a succession of management practices in the same place as time goes by (e.g., annual rotations). Flows are more complicated when considering the animal component due to spatial mobility and biomass transfer.

Types of flow, as well as inherent energy and economic costs, depend upon the system and the spatial scale. Nitrogen flow, for example, may occur at the scale of: (i) a field, using legumes in rotations to enrich the soil; (ii) the farm, with production of protein sources to feed livestock; or (iii) a region, with waste transport between production systems or industries, some with a surplus and others unprofitable.

Spatial flows also condition management steps, such that social systems work in different ways and at different scales (farm, community, region, etc.). Therefore, development and adaptation of integrated systems must be analyzed, not only in agronomic and biophysical terms, but also in social and functional terms. We cannot develop a spatial approach without considering the managers of that space, i.e., the social actors.

The rural landscape concept consists of a spatial structure and social scale where the components of an integrated system are located (crop land, pasture, forests, livestock, decision making and flow managing groups). We used the rural landscape as the analysis level in this study, allowing spatial and social dimensions to vary from one case to another in the tropical region.

Methodology

This analysis represents the work of a large team located in three continents with many years of scientific cooperation in agro-ecosystem and interdisciplinary research. With on-going expansion and adaptation of integrated systems in the tropics, we gathered and shared our experiences over the past few years from various analyses at each location. This individual approach did not allow *sensu stricto* comparison of results produced by a standard methodology, but aimed to build perspectives based upon refined and adapted analysis at each location. We describe successively three contrasted case studies, allowing readers a transverse and illustrated view of agro-ecosystem diversity in the tropics.

The spatial dimension was the focus of our descriptions of integrated systems within a landscape context, complemented by historic analysis of its development as a way to understand the essence of mechanisms and local adaptation. Table 1 synthesizes the details of the systems in each area studied.

Data collection in the three regions occurred in a distinct way, aiming for specific goals within each project. However, all projects contained information on flow paths, spatial dimensions, historic construction and management of rural landscape and associated social systems.

In Soudanian Mali, a broad database was developed in 2006 and 2007 from eight villages in the cotton belt in the districts of Koutiala, Sikasso, Bougouni and Kita[8]. A survey was conducted in all farms (826) of the eight villages. From a multi-criteria typology, a sample of ten farms in each village was selected. The subsample represented a diversity of practices regarding soil management, livestock feeding and diversity of farming production. All 80 farms were documented closely during 12 months, with type and quantity of farming operations evaluated for main operations, from herd management to biomass flows among cultures, pasture, herds and bush community areas. Labor from family and hired workers and financial budget of the farm were studied. The frequency of observations on each farm was every 15 days, and additional data were collected occasionally, such as in harvest season or from organic fertilizer applications produced on the farm. Other group and retrospective interviews were conducted in every village, referring both to the history of the practices, as well as to the community and natural resource management. Satellite images (Aster) were analyzed to map the main components of the rural landscape in each village.

Collection of data was less intensive in the Brazilian savannahs (*Cerrados*). Flow paths involved corn and soybean farmers, cereal crops, poultry, swine, beef and dairy farmers, slaughter houses and chemical dealers[9]. These flows were not directly collected by the team, because data were available in the literature from a doctorate thesis in agricultural sciences, as well as in various technical papers from both private and public local institutes[10]. The team mobilized the concepts of marketing chain and territory to characterize the social system that managed the integrated flows. Interviews were conducted with individuals from various sectors: 23 representatives of the local community, 16 public institutions and banks, 9 ethanol plant production managers, 29 crop and livestock farmers and 15 members of the slaughter and food agro-industrial complex[9]. For every sector, a questionnaire was developed, highlighting two levels of analysis, i.e., the production chain and the practices or specific activity of each sector. An interview lasted *c.* 2 h and was organized for 1 year between 2009 and 2010.

In Amazonia, information was gathered during a long period, not in discrete events as in other fields of study. Since the mid-1990s, the team conducted studies of land use in three pioneer frontiers in the State of Pará (Brazil): Transamazônica, Southern Pará and Northeastern Pará[11,12]. Eight doctoral theses were realized by the team concerning the livestock expansion theme, focusing on degradation caused by pasture management, production chain and spatial dynamics, diversification of production and specialization of farms, dairy management practices and economic analysis of livestock systems. In 2011, a campaign of 38 interviews was conducted in the three regions, aiming to analyze the dynamics of livestock production and diversification of land use in response to deforestation policies[12]. Consequently in 2012, a land diagnosis was made in the municipality of Paragominas, combining 70 semi-open interviews with key informants (30 at the institutional level and 40 in communities and with farmers) and 160 interviews conducted survey-style in rural establishments. This information was intended to diagnose the role of family agriculture on land development and to analyze the dynamics of pioneer frontiers on integrated agriculture in the Paragominas.

Integrating the Spatial Dimension of the Three Case Studies

The three case studies were diverse in their description of farming production and level of integration. All three cases were described from an historical perspective. By understanding the current spatial dynamics and management of farming systems in these case studies our analysis sets the stage for building integration processes. Knowing the structure of farm conditions allows us to better understand its dynamics. However, we also wanted to discuss the perspectives and future situations, taking the reader beyond the observed situations. Therefore, our approach followed three stages:

(i) Historical description of systems and formation into the current condition.
(ii) Description of changes and management affecting such changes.
(iii) Perspectives on the advantages and limitations of the current system.

With uneven availability of data, the approaches we took had to vary. Contrasts among the integrated systems help enrich our understanding of different approaches.

Village systems in the Koutiala Cotton Belt of Southern Mali

Forty years of development from slash and burn to integrated systems. In Southern Mali, agro-systems are organized along toposequences: landscape relief determines the type of soil and its potential for production, whether native or cultivated[7]. Due to water flow in the watershed, upland portions have more fragile soils, with coarse texture and low fertility, while lowland sections of the watershed have deeper soils with a higher percentage of clay and fertility[13]. Sociologically, village residents sort along the toposequence by inhabiting the uplands[14]. In each village, native vegetation areas are community

property, and therefore pastures and forests are used communally. Cultivated land is managed privately during the crop production season, but communally during the non-growing season[8]. A village leader defines the rules for common use of these areas[15].

Up to the first half of the 20th century, farming practices were based on the slash and burn system, with regeneration cycles of about 20 years. At that time, upland portions of the toposequences were preferentially cultivated due to finer vegetation that was easier to clear[16]. The low chemical fertility common to such soils was compensated for by the return of ashes from burned forests, which was also a technique to make the land easier to work. Local farmers did not own cattle at this time, and therefore, there was no crop–livestock integration. Cattle herds were managed by migrant ethnic groups from the northern regions of the Sahel.

During the past several decades, with the introduction of large cotton companies, land has been managed with the 'cotton technical package' using plowing with animal traction and improving soil fertility, with a strong impact on the rural landscape[17]. In this contemporary system, the regeneration stage (also known as bush fallow) has largely disappeared, such that fields are permanently cultivated and the forest is disappearing from the landscape[14]. Crops are now predominantly grown in the clay-rich lowland areas, since the plow and traction bulls have made it easier to work these deeper soils[18]. With greater water retention, these fine-textured soils have helped overcome susceptibility to drought in this area with large precipitation variability[19]. Another advantage of the current system is that chemical fertilizer applications have produced greater cotton crop yields, positively affecting corn and sorghum grain grown in the typical rotation. In forming these permanently cultivated fields, some trees have been preserved from deforestation, such as the karité (*Vitellaria paradoxa*), néré (*Parkia biglobosa*) and even mango (*Mangifera indica*). Now there are 'savanna parks', with random trees growing in cultivated fields in these lower areas[16].

Livestock production became more directly integrated into the system, initially with traction bulls[20]. Small cattle herds rapidly developed with available revenue coming from cotton sales. In a short time, the region became attractive to farmers with animal husbandry talents. More favorable precipitation in the Sudan than in the Sahel also made it possible to produce superior forage for livestock production[19]. *Trypanosoma* has been a limiting factor to cattle production in the area, but has diminished due to deforestation of the humid lowland areas, as well as the use of adequate veterinarian products. Thus, cattle often grazed upland vegetation that was more abundant and of high quality, of species such as *Andropogon gaianus*, while lowland native vegetation was spared from deforestation.

These animal and plant components began to work interchangeably, integrated, under the compound effects of demographic growth and ongoing deforestation[20]. With consolidation of permanent fields, limited quantities of chemical fertilizers distributed by agri-business became insufficient to correctly manage the soil. Farmers were interested to utilize manure from cattle herds to improve fertility of cropland soil, such that cropland became an essential part of the fodder calendar, especially in the dry season, whereby grazing cattle deposited feces directly on cropland. With expanding cattle herds, upland pastures became excessively utilized, resulting in overgrazing and rapid degradation of pasture resources[21]. Today *A. gaianus* is virtually extinct. Many innovations were implemented in the integration of crop and livestock systems in all villages of the Malian cotton belt[22].

Managing and recycling crops, fodder and animal manure. In the current system, nutrients are recycled through cattle manure, household waste and crop residues. Similarly, corn, sorghum and peanut residues are used to complement perennial grassland and arboreal forages for livestock fodder[23]. This recycling of nutrients between organic fertilizers and forage is made from rural facilities, such as pits for manure production and storage areas for forage[7]. Carts are essential for biomass transport between places of production, processing and application. Figure 1 schematically depicts these flows.

It is clear that in this new scheme, biomass recycling is the core of animal and plant productivity, as well as the owner's investment and labor use. Management takes into account the spatial structure of the property, since fields are spread across the toposequence, as allocated by traditional authorities and family heritage. Thus, each property has a unique spatial distribution among the three types of fields (non-manured fields, manured fields and bushland) and size of cattle herds[24].

Integrated management combines characteristics of each portion of the rural landscape with biomass flow (e.g., distance and type of soil) and characteristics of each property (e.g., equipment for transportation and processing, harvesting labor, processing and biomass distribution). In addition, there are community decisions at the village scale, mainly to regulate access of livestock to communal pastures and on crop residues after harvesting, but also for the use of fire[22].

Land carrying capacity at stressed condition. Nowadays, many villages in the northern part of the cotton belt face a crisis from this integrated system due to a natural limit on land carrying capacity. Production of each component is now insufficient, given human population density (demand for food) and bovine density (overgrazing and lack of forage). The amount of biomass involved in integration has been decreasing beyond necessary thresholds for sustainability. The necessity of growing food for families to achieve food security leads farmers to expand cultivated areas permanently at the expense of perennial pastures[25]. As a consequence, the ability of farmers to feed cattle near to villages is decreasing, and herds now tend to spend long months in distant regions that are more

Table 2. Indicators of productivity at the village scale in three contrasting southern Malian situations.

Agrarian system	Village name/district	Human density (persons km^{-2})	Cattle density (tropical bovine units ha^{-1})	Cultivated areas (%)
Slash and burn	Biliko/Kita	17	0.07	10
Integrated system	Bohi/Bougouni	51	0.29	24
Crises of integrated system	Baoufoulala/Kinian	58	0.32	36

Adapted from Poccard-Chapuis et al.[8].

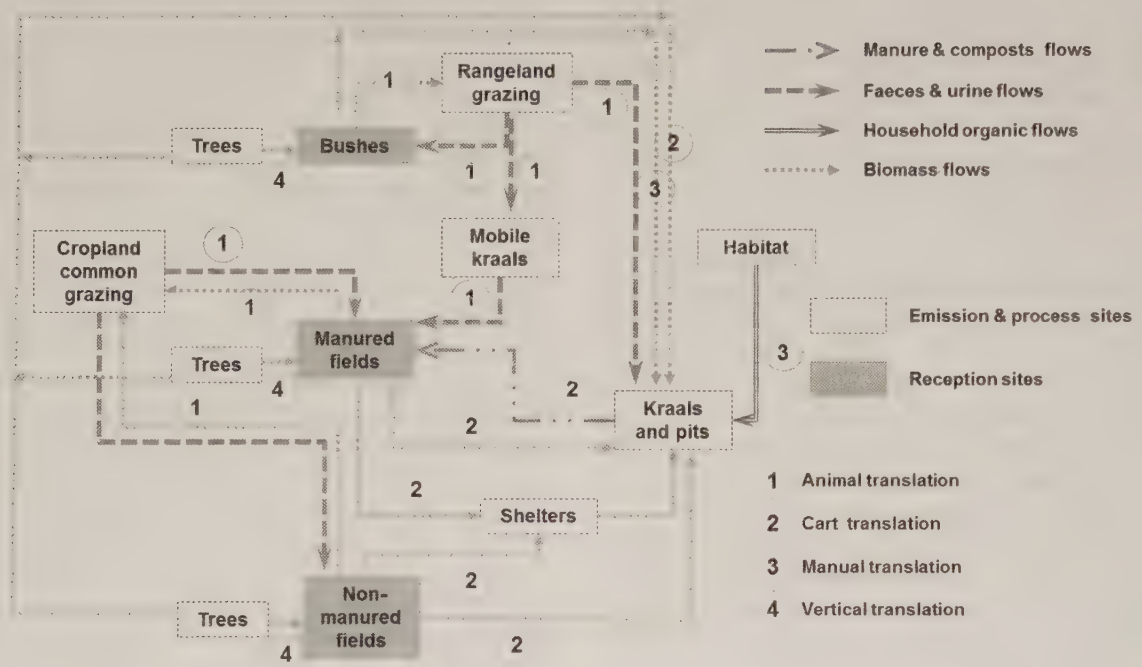

Figure 1. Integrated flows of nutrients in Southern Mali farms. Adapted from Lemaire et al.[24].

favorable[26]. This separation decreases the ability to fertilize cropland soil and overall productivity of the territory declines.

Table 2 shows the productivity gains that the integrated system provides at the village scale, mostly related to the previous cut and burn system. It also indicates a maximum productivity ceiling, marking a crisis in the system.

Rio Verde de Goiás in the Brazilian Cerrados

System developed from successive agricultural colonization. In the Brazilian *Cerrado*, integrated systems work differently, despite having been implemented around the same period and a comparable natural environment. Native fields grazed by cattle herds with extensive ranching since the 17th century[27] were converted into cultivated pasture in the 1950s, notably with *Panicum* species, and since the 1980s into fields for permanent crops (rice, corn and soybeans). Homesteaders from the south of the country were encouraged by public policy to inhabit the *Cerrados* by receiving 500 ha parcels of land. In the late 1970s, large companies introduced a technical package for soybean, based on no tillage and use of chemicals to fertilize the soil and reduce labor. After 3–4 years of corn and soybean crops (two crops per year), they planted a perennial forage grass, *Brachiaria*, for cattle fattening[28]. The pastures received the carryover effects of fertilizers and soil corrections. This was a great technical and economic success with good harvests and low production costs, all of which transformed the *Cerrados* into one of the largest soybean and beef production areas of the world[29].

However, the level of integration between crop and animal production was low, only by indirect pasture fertilization with chemical inputs applied to corn and soybeans crops. Everything changed when one of the largest national poultry companies demonstrated some interest in the region.

Introduction of an agro-industrial system integrated at the regional scale. The abundant and relatively inexpensive supply of plant protein products has helped create a large agri-food industry by the company Perdigão, known nowadays as Brasil Foods, which has become the largest

poultry producer in Latin America. The company has chick production plants, feed production, slaughtering, meat processing and conditioning, and a park of 900 aviary modules, distributed in the region. The company coordinated a large-scale transformation of domestic soybean protein into animal protein via chicken production for meat export[10]. Later they also developed swine production for the domestic market. Nowadays, Brasil Foods slaughters 450,000 birds daily. Soybean and corn are purchased from local farmers and turned into feed, then sold to 226 poultry producers, each with a flock of 100,000 birds. The birds are bought and slaughtered by the company, which exports frozen processed meat[9]. Thus, Brasil Foods has developed an agri-business paradigm based on crop–livestock integration.

The last step of integration was with animal manure valuation. Unlike in Brittany France, where the density of farms with monogastric livestock is very high, causing excessive manure production and pollution of the environment, available land area in the Brazilian *Cerrado* is abundant (20,000 km^2) and sparsely populated[30]. Therefore, the nutrient-rich manure is scattered onto pastures, which recycles nitrogen and contributes to other forms of animal production. The fertilized forage by manure from monogastric livestock allows ruminant livestock to graze pastures with weight gains of about 1 $kg\,ha^{-1}\,d^{-1}$.[31]

Technical optimization of the integrated system with competition from macroeconomic and regional issues. With the success of the crop–poultry integration model, Brasil Foods is planning to add another module to the chain, with dairy. Manure application to pastures builds fertility and opportunity for ruminant production. They plan to stock dairy cattle on pastures at 5 animal units $ha^{-1}\,yr^{-1}$,[9] and to develop an industry–farmer partnership system similar to that for the poultry module. This strategy will cover a large radius surrounding processing facilities ($\sim$ 80 km), enabling efficient grain, animal, manure and meat transport. Farms practice among themselves only mild levels of integration, but management of the flows (food, feed, animals, manure and fertilizers) by the company will enable multiple levels of integration. The boundaries of the territory being integrated are clearly economically driven and managed by the company.

Table 3 shows some productivity indicators at a regional scale, and the volume of integration in the Brasil Foods complex of Rio Verde de Goiás.

Despite the technical, economic and social efficiency of the integrated system, it has been threatened by two external processes. A sugar cane belt, located further south in the state of São Paulo, is expanding rapidly due to favorable infrastructure and market conditions. Croplands in Rio Verde are now having competition for use with sugarcane. Reduction in grain and pasture production could disrupt the integrated structure and affect performance of the agri-business company. Moreover, the construction of a railway linking the region with river and sea ports for export could increase grain prices that producers receive (thus negating the advantage Brasil Foods receives by purchasing local grain), since transportation of grain currently by truck is more expensive and consumes part of the cost of production. Therefore, the company may lose one of the main advantages of its presence in the territory: the existence of an abundant and cheap raw commodity. To keep the advantage, they would have to move northward into the Brazilian Amazon, where there are other grain production regions, but still isolated from major transport routes. Thus, we see that the technical system of integration bumps into the dynamic social system in which it operates.

Table 3. Indicators of productivity at the regional scale in the Brasil Foods basin of Rio Verde, Brazil.

Area involved in integrated system (km^2)	20,000
Human population density (persons km^{-2})	21
HDI[1] in 2000	0.807
Brasil Foods direct jobs	8500
Brasil Foods chicken production (head d^{-1})	450,000
Brasil Foods pig production (head d^{-1})	5600
Brasil Foods turnover (US$ yr^{-1})	1,250,000,000
Animal feed production (ton yr^{-1})	2,775,000

[1] Human Development Index.

Paragominas in the Amazonian frontier

Five decades of land degradation with deforestation. The Brazilian Amazon is animated by several agrarian dynamics. We focused our approach on the pioneering regions of the agricultural frontier requiring deforestation. This frontier is dynamically under construction, integrating the mechanisms of development of the national territory[32]. The municipality of Paragominas is one of the most advanced on this path toward integration.

Settlement of this region is marked by the process of land ownership, or 'land struggle', in the now famous expression of Schmink and Wood[33]. Pioneers from other regions of the country, as well as indigenous people, seek opportunities to accumulate assets and develop agricultural production[11]. In this frontier, social institutions and supply chains are not consolidated and functioning[32,34]. Selfish behavior prevails in social relations and in agricultural production structure[35]. During the phase where territories are in the early stages of development, the only level of functional organization is the farm. In the early decades of settlement, the journey of pioneers is based more on land ownership, land hoarding or speculation, rather than in the pursuit of sustainable integrated crop and livestock production systems[36]. From technical and social points of view, at least initially, extensive cattle ranching is one of the few opportunities within reach of pioneers to achieve their goals, both for large and small producers[37]. This reality has led to

widespread specialization in this activity. The settlement process with cattle ranching occurs without taking into account the characteristics of land relief, soil and moisture[11].

Deforestation has been followed with widespread planting of *Brachiaraia bryzantha* as pasture forage, although not always with establishment success, leading to low forage productivity[38]. Inadequate management of pastures causes oscillation in the number of animals and the need to clear new areas, typical of pioneer systems[39]. Fire is often used in old pastures to try to control weeds[40]. Low productivity pastures have led to the 'devastation of the Amazon', resulting in ~70 Mha of monoculture pastures of low productivity per hectare (about 0.7 tropical bovine unit ha^{-1})[41].

Origin of new and dynamic integrated conditions. Federal policies from the 2005 Plan for Deforestation Prevention and Control (PCDAM), reinforced by the vote of the forest code in 2012, have resulted in a set of rules and mechanisms regulating loggers, farmers and various stakeholders of the bovine and timber chain[42]. Heavy fines, police operations, satellite monitoring and environmental compliance obligations administered by the Justice Department have forced stakeholders to comply with these rules, leading to a sharp decline in deforestation and the use of fire. In parallel, some territories and infrastructure were developed, allowing new land use for grain, oil palm, eucalyptus and fruit production. Cattle ranchers were forced to focus on the most favorable pasture areas from the point of view of fertility and logistics. Innovation to increase forage production from less area has become necessary, especially with the emerging concept of ecosystem services and the negative image of deforestation. A new relationship between livestock and people is under construction in the Amazon[12].

Crop–livestock integration, non-existent until recently, has been seen as a solution for the region. Two different integration approaches are emerging to reform systems specialized in livestock. Both occur on the scale of the farm.

Crop–livestock integration. Integration in many cases is seen as a solution for recovering degraded pastures, as well as diversifying income for the farmer. Cultivation of soybean and corn in a period of 1–5 years is promoted as a technical package with no tillage or conventional tillage and chemical inputs to fertilize and control weeds. After the crop period, improved grass is planted and high productivity pasture is formed due to residual soil amendments from cropping. The system is repeated in other portions of the farm over time until the entire pasture area is renovated. The farmer may also choose to plant trees for fruit and wood, as a way to generate an income in the long term and improve animal health and productivity. There is also an option to outsource the cultivation of grain, or rent land to plant commercial trees, to a specialized company.

Role of trees. Some integrated crop–livestock–tree systems have been developed. Apart from their own economic value to provide wood or fruit, trees may contribute to fertility of the soil in the case of legumes that fix nitrogen, as well as to protect crops and animals from heat and wind. Water stress during the dry season is a major limiting factor for forage production, increasing the risk of accidental fires. Furthermore, only the Nelore zebu is fully adapted to tolerate direct sun in the equatorial region, but productivity of meat and milk can be greatly enhanced with cross-breeding with European breeds. The absence of shade in pastures can prevent cross-breeding. Thus, silvopastural systems can be beneficial. Several arrangements exist in planting trees in strips, groves or thinning of woods, with varied spacing between trees. The most planted species are eucalyptus (*Eucalyptus urophila*) and the paricá (*Schizolobium amazonicum*), which have high productivity and are well accepted in the domestic market (coal to steel, plywood furniture, pulp for the paper industry). Many other species have potential, but cultivation is limited by availability of seeds and expertise.

Introduction of trees in the pasture also occurs spontaneously in the process of pasture degradation. Some species, such as babassu (*Orbignya phalerata*), considered invasive, are prevalent in pastures and assume roles of wind breaking and shade. Others, such as the *Ipê* (*Handroanthus* spp.), are often found due to selective grazing and where the producer seeks to preserve species considered useful.

Synthesis

Based on the three case studies, we describe four key issues to better develop integrated crop–livestock systems in the tropics.

Optimizing spatial organization of crop and livestock components within the landscape

Rural landscapes have inherent physical and functional characteristics that determine to some extent necessary spatial structure. Functional improvements in rural landscapes can occur over time and with consideration of crop and livestock components in space[43].

In the Paragominas case, rural landscapes are still largely at an early stage of development following the removal of native vegetation. Spatial arrangements have not yet been refined due to the broad approach of deforestation and grassland cultivation, in which social considerations have outweighed environmental decision-making. Productivity gains through arrangements of various components in the landscape are potentially high, considering the challenges from recovery of degraded pastures and formation of eco-efficient landscapes. Besides, reforestation in areas of permanent preservation is now required by law, and farmers will

need to identify critical parts of their farmland, such as relief, soil, distance, wetland and river network, in order to develop an efficient spatial arrangement of land use and appropriate management practices for optimizing biomass and water utilization. More than a static form, this arrangement should be thought of as a process of progressive pasture reform, with occasional diversification into other uses. Greater appreciation of where animal manure is deposited (i.e., on pasture for temporal rotation with cropland or in corral for collection and spreading on cropland) is needed.

Silvopasture systems are gaining acceptance in the international development community. Tree, livestock and forage components interact over time in the same area, with shade and soil fertility interactions of key importance. Productivity per hectare can be high, given mobilization of technology, knowledge and inputs, and environmental impacts of agriculture can be minimized due to more closed nutrient cycles.

In the case of the Brazilian *Cerrado*, spatial arrangements and nutrient flows are being optimized for productivity. However, this highly specialized form of crop–livestock integration has high environmental costs, with the extinction of native vegetation and little preservation of surface water. The integrated system is clearly based on strong manipulation of the landscape, from chemical inputs, cultivation of exotic species and full monitoring of agro-ecosystems. A challenge from the spatial point of view would be to release productive areas to the re-establishment of native vegetation, primarily not only in wetlands and river valleys, but also in some upland areas. There is also a risk of further diversification in land use, in which farmers may choose to plant sugar cane, and thus create unbalanced cycling among animal and crop production and biomass recycling.

In the Malian case, spatial arrangements are well optimized. To improve biomass production and avoid crisis situations, some land areas and times could be better managed, such as open areas between cultivated fields or during the agricultural calendar (after corn harvest, for example, or early dry season). Availability of labor becomes a limiting factor in some farms. Another option may be for farmers to maintain private control of croplands following harvest to be able to generate more organic fertilizers directly on the land rather than lost to wandering herds. Another option for improvement is to temporarily ban grazing of some forage banks, which could then be used during droughts for cattle feeding.

Role of institutions in integrated management

The three study cases show contrasting management structures: management by an agro-industrial company (Rio Verde de Goiás, Brazilian *Cerrado*), management by the farm (Paragominas, Brazilian Amazon) and combined management by farmers and community authorities (Koutiala, Mali).

It is interesting to compare the specific cases of Mali and the Brazilian *Cerrado*, with similarities from an ecological point of view but totally different from the social point of view, on the productive performance of the integrated systems. Management by the agribusiness company in the Brazilian *Cerrado* certainly facilitated several factors that Malian farmers lacked: finance access, equipment and technical support, quality inputs, training and complementarity among specialized components. Brasil Foods was able to mobilize public policies to support its project, particularly public funding for infrastructure development. However, above all, it completely leads the integrated system, by the direct control of livestock (number of birds and swine) and indirect influence on cultivated areas (e.g., prices paid to farmers), feed production, meat production and making components complementary. The company can monitor and adjust crops and livestock in the territory, as well as biomass circulating in the integrated system. Even transportation is managed by the company with a fleet of trucks and a dense network of passable country roads. Brasil Foods was responsible for assembling and balancing this system, economically and agronomically coordinating it in an effective way. However, this integrated structure has the risk that farmers may invest in other production systems, such as sugarcane as has been attractive in neighboring regions. It is possible that a decline in grain supply would lead Brasil Foods to forego the territory and move its activities to another region. This is one limiting factor in managing a large corporation: it can optimize an integrated crop–livestock system, but it can also change strategy and withdraw, compromising the development direction of the territory. Therefore, the social system may be influenced by an uncontrollable external agent, affecting the viability of an integrated crop–livestock system.

In the Mali case, where virtually none of these features exist, management was left to the farmers themselves and traditional authorities. Biomass production, transport and transformations are limited by the lack of investment, fertilizer, feed and processing plants. Connection to public policy is weak, limiting the impact on and from the agrarian system. Moreover, traditional management has difficulties in promoting technical innovations, such as controlling grazing on community land. This comparison clearly shows the role of managers in innovation, public policy mobilization, and management and tactical integration. The social system in villages combined with the former slash and burn and forest succession system can be considered hindrances to optimizing integrated systems at a regional scale. The trend is that farmers, as seen in the Amazon case, end up developing integration individually without collective mobilization of potentially shared resources and biomass.

The Amazon case of Paragominas is also noteworthy when it comes to integrated management. It shows the limits of a system managed individually at a property

Table 4. Occurrence and characteristics of tree species found in 41 pastures in Maraba, State of Pará, Brazil.

Name	Frequency (%)	No. of trees species per pasture	Utilization	Farmer monitoring
Attalea speciosa	74	3	Cooking oil and cosmetics	Yes
Spondias mombin	11	4	Fruit juice	No
Apeiba tibourbou	9	7	Fiber	Yes
Tabebuia impetiginosa	8	4	Hardwood	No
Stryphnodendron guianense	8	5	Fertilizer–fodder	Yes/No

Adapted from Alves et al.[40].

scale, to develop integrating systems and innovations in general. Some innovators may be able to master the technological leap for annual cropping, forestry and cattle production in combination, but we cannot say that this is common. Many farmers are not able to get this type of information and integrated technology package easily, so the contribution of public and private institutes seems essential. Technical assistance and rural credit are needed. In another approach, rather than individual scaling of integration on each farm, integrated systems can be developed spatially within a region, similar to the example in the Brazilian *Cerrado*.

Reliance on internal rather than external resources

One of the arguments for the development of integrated systems could be the substitution of imported chemical fertilizers from distant areas by local biomass. The three study cases partially confirm this characteristic, each in a different manner, pointing to improvements.

In the Rio Verde of the Brazilian *Cerrado*, there are virtually no biomass imports, except for seeds and chemical fertilizers. The structure works in a closed circuit, unlike other large monogastric production areas of the world. This reduces costs and limits negative environmental consequences. Manure management is made easier due to the large integrated scale structure: organic materials can be treated as fertilizer on abundant pastures without stockpiling to become toxic. This is certainly the biggest success of this model of agricultural production. However, reliance on external inputs is still strong, including pesticides and fossil fuels. In addition to environmental concerns with removal of natural ecosystems, public support of farming regions without concern for biodiversity may diminish, leading to future legal restrictions on marketing of food products. The economic cost of reducing external inputs would likely be high, with decreased productivity. This system is typical of an agri-business cluster whose competitiveness comes from expertise and a focus on productivity.

The inverse problem exists in the Soudanian Mali belt. The integrated structure is based on local biomass recycling, with a few external inputs to the territory (except cotton seeds and small amounts of fertilizer and herbicides). Farmers of this part of Mali build new knowledge locally to develop innovative integrated systems with their own resources. Vigne[44] proves the high energetic efficiency of these systems from the low use of inputs, lack of fossil fuel use through machinery, reliance on human labor and local biomass recycling. Greater use of external inputs, such as fertilizer and forage concentrates for herd concentration, could increase biomass production and the ability to recycle even more biomass. However, the cost of these inputs is still too high for farmers in this region.

Table 5. Number of herbaceous shrub species found in 41 pastures in Maraba, State of Pará, Brazil.

No. of herbaceous species	20–29	30–39	40–49	50–59	60
No. of pastures	0	2	5	15	21
% of pasture	0	5	12	35	49

Adapted from Alves et al.[40].

In Paragominas, the situation is in the middle ground. Deforestation is a huge artificialization of the ecosystem, with great impacts on the water cycle, biodiversity and greenhouse gas emissions. However, plant communities that have developed with extensive livestock systems have interesting ecosystem service characteristics from the integrated system point of view. Almeida[45] estimates that 20% of the deforested area in recent decades is derived from secondary forest after abandonment or fallow. Pasture degradation processes eventually lead to greater plant biodiversity[39]. Alves[40] noted the strong presence of trees in pastures in the Amazon, as well as a great diversity of herbaceous shrub species. Plant communities in Amazonian pastures are rich, as shown in Tables 4 and 5, with pastures initially established as monoculture forage species, natural succession of leguminous shrubs and trees in pastures certainly bring benefits to the production system. Some farmers intentionally monitor diversity of grass species, concluding that the livestock diet can be improved with limited intake of *Bracharia bryzantha*. Pasture diversity may also assist the functioning of soil, humus formation and provision of shade for animal comfort and productivity. Rural landscapes in the Amazon already have favorable characteristics for the development of improved integrated systems.

Since many producers do not have access to inputs, technology and assistance, and the landscape and climate are conducive to multi-layered plant communities, optimizing existing landscapes with internal resources only makes sense. Farmers have local knowledge about trees and leguminous shrubs found on their property. These resources dispense the need for external inputs and seeds, economic risks and investments. After the trauma of deforestation, the scientific community and farmers' social networks need to develop further innovations in local agro-ecosystems, without necessarily thinking of artificial technology and external inputs.

Nitrogen flows

The example of the Brazilian *Cerrado* shows the importance of nitrogen flows to enable development of integrated systems. Whether for soil fertility or feed, nitrogen as the basis of protein is essential to increase productivity in crops and livestock. Recycling of nitrogen is a key for high system performance in the *Cerrado*.

Nitrogen is a limiting element in the other two cases studied. In Mali, primary production of plant protein is very low. Soybean, as a nitrogen-fixing grain legume, is not cultivated. Peanut is also a nitrogen-fixing food crop that typically occupies a minor role in the crop rotation. Leguminous trees are rare and have low productive potential for human or livestock consumption. Production of monogastric livestock is limited and feed is based on household waste and rambling. Biomass transformation is primarily through ruminant intake and meat or milk production. Cultivation of leguminous crops helps meet food security of farm families. Crops are almost exclusively for human consumption or for sale (e.g., cotton). Harvesting the non-edible portions of bean (*Canavalia ensiformis*) and velvet bean (*Stizolobiun aterrinnum*) could foster the development of production of small ruminants and poultry, thereby increasing the recycling structure for soil fertilization.

In the Amazon, nitrogen is more abundant, but less valued in integrated flows. As explained above, the leguminous trees and shrubs are present in pastures. However, pasture improvement tends to eliminate them, focusing only on the grasses planted. Forage mixtures with pueraria (*Pueraria phaseoloides*), estilosantes (*Stylosanthes* spp.), galopogonios (*Calopogonium mucunoides*) and arachis (*Arachis pintoi*) are still unpopular. Either way, nitrogen flow is usually directly from the decomposition of plant parts to the soil without animal transformation via grazing. Production of high-protein forage is limited, but when it is produced it is mainly for cattle. Manure is often not collected and recycled as fertilizer. Production of monogastric livestock has obstacles in access to grain, which is limited in the region where pastures dominate. Relative specialization of farms suggests that integration and nitrogen recycling are not strong within a farm, but could occur within a territory between specialized farms producing crops, monogastric livestock and cattle. A limiting factor is the presence of an industry to produce feed and meat through transformations and management of biomass flow.

Conclusion

The spatial approach we undertook allowed evaluation of different technical and sociological characteristics of farming systems in the tropics, as well as understanding of the material flows in integrated systems. Management of farms and farm communities in the rural landscape helped to frame the evaluation. We characterized the historical development of landscape characteristics in three different cases to better understand the possibilities for development of integrated crop–livestock–forestry systems in the tropics.

The rural landscape supports biomass and nutrient flows at levels of plot, property, village, belt production and region. Each level can be managed, but the type of social structure may limit influences for change to a more sustainable integrated system. Integrated systems cannot be viewed as universal models, but as a concept to adapt to each agro-ecological and social situation, unlike the current trend to develop 'models' of integration. Another limiting factor of these models is that they are usually designed to increase productivity from innovative solutions, artificial or at least external to local realities. However, there are enough elements in the agrarian history of each region, and its current landscapes, which can serve as a base for more endogenous integrating systems, less artificial and, therefore, more suitable to local agro-ecological and social systems. In both cases, since the integrating systems have a large spatial extent, development or improvement requires the involvement of local institutions and coordination of actors. Thus, research initiatives toward integrating crop–livestock–forestry in tropical regions should not only focus on technical and production factors, but assemble interdisciplinary teams addressing social and landscape analyses.

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Comparison of an integrated crop–livestock system with soybean only: Economic and production responses in southern Brazil

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Abstract

In Brazil, as well as globally, land use has been increasingly addressed for environmental impacts and economic improvements. Integrated crop–livestock systems (ICLSs) are a potential strategy to optimize use of land, increase total production and reduce economic risk through diversification. We compared production and economic outcomes of a soybean-only system with ICLS differing in sward management. The study area was managed since 2001 using no-till in southern Brazil. Soybean [*Glycine max* (L.) Merr.] was rotated with a mixture of black oat (*Avena strigosa* Schreb) and ryegrass (*Lolium multiflorum* Lam) either for: (i) grazing (ICLS) or (ii) cover crops as cropping system only (CS) with no livestock grazing. Four sward height management methods (10, 20, 30 or 40 cm) were evaluated under put-and-take stocking. Across years, soybean yield ($2516 \pm 103\,kg\,ha^{-1}$) was not affected by treatment, but was affected by year ($P < 0.001$), due to rainfall during crop development. Cattle average daily gain, gain per hectare (GPH) and gross margin were affected by treatments ($P < 0.001$). Average daily gain was lower when pasture was managed at 10 cm than between 20 and 40 cm. With increasing sward height, a gradual reduction in cattle GPH was observed ($P < 0.05$). Overall gross margin was lower in CS than in ICLS. Economic return with ICLS was greatest when sward height management was between 10 and 20 cm. Our study indicates that ICLS could be considered an alternative management strategy that improves economic performance and promotes balanced production in the long term.

Key words: mixed systems, sward management, financial analysis, no-tillage

Introduction

Management of grassland ecosystems has been the focus of research on food production, livelihoods and ecosystem services[1], with a goal of reducing environmental impact and improving economic value of these systems. Among alternative systems, one strategy is an integrated system of crop and livestock production. Integrated crop–livestock systems (ICLSs) are a challenge for farmers because of the difficulties in managing complex interactions between grain and livestock production during different seasons in a single area. In addition to maximizing interactions between crop and livestock production, ICLSs benefit the environment by enhancing nutrient cycling[2,3], and are considered a good way to achieve sustainable intensification of agricultural systems[4].

During the 1990s, research in Europe on integrated systems focused mainly on crop production, where the use of crop rotation was successfully implemented to reduce fertilizer and pesticide use[5,6]. Recent studies have shown that the integration of cattle and pasture with a grain crop rotation increases the quantity and quality of soil organic matter in comparison to continuous cropping[7,8].

In many regions of Brazil, there are degraded pastures that could benefit from integrated systems to increase agricultural output. Southern Brazil has 6.4 million hectares annually cultivated with soybean [*Glycine max* (L.) Merr.], maize (*Zea mays* L.) and rice (*Oryza sativa* L.)[9]. In the past few years, approximately 1.1 million hectares have been cultivated with winter crops such as wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.) and barley (*Hordeum vulgare* L.)[9]. The remaining area

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(i.e. 5.3 million hectares) without crops in the autumn and winter seasons, represents potential income with soil being exposed or simply seeded to cover crops[10]. An ICLS is a potential strategy to increase production in these areas and reduce financial risk for farmers through diversification. Producers make decisions about adopting alternative systems based on the price outlook for products, which can fluctuate both in the short and long term. Nevertheless, farmers are generally most concerned about deviations in yield below the mean or other target values[11,12]. Therefore, investigating ICLSs using both economic and production values is a key step to assess the performance of integrated systems over specialized systems.

When a farmer decides to adopt ICLS, a relevant factor is the use of adequate grazing intensity during the pasture phase, which is a key management variable influencing sward structure. Grazing intensity affects animal performance by influencing herbage intake through modifications in sward structure[13], as well as possibly affecting crop development by physically altering surface soil or changing nutrient recycling[10].

In general, farmers often use high grazing intensities and set stocking rates greater than pasture carrying capacity, which can negatively affect both pasture and crops in the rotation[10]. Determination of an optimum stocking rate must be balanced from trade-offs among several potential outputs that may conflict[14]. There is evidence that grazing management promoting higher individual animal production (i.e. moderate grazing)[15] can also foster positive environmental outcomes[16].

The objectives of this paper were: (i) to compare production and economic outcomes from a soybean cropping system with and without cattle grazing; and (ii) to analyze different sward management strategies for ICLSs, to determine optimal sward height.

Materials and Methods

Study area

The study was conducted at Espinilho Farm (28°56′14.00″S, 54°20′45.61″W) in the state of Rio Grande do Sul, southern Brazil, between May 2001 and April 2012. The climate type is Cfa according to Köppen, humid subtropical with hot and humid summers and cool and humid winters[17]; similar climates are found in the USA, primarily in the southeast. Climate data (Table 1) were taken from a nearby station maintained by the Agricultural and Livestock Research Foundation of Rio Grande do Sul, Brazil.

The soil at Espinilho Farm is classified as Rhodic Hapludox (Oxisol) with 540, 270 and 190 g kg^{-1} of clay, silt and sand, respectively, at 0–20 cm depth. The experimental area was managed since 2001 as an ICLS using no-till. Soybean [*G. max* (L.) Merr.] was rotated with a mixture of black oat (*Avena strigosa* Schreb) and ryegrass (*Lolium multiflorum* Lam) with or without grazing. After inoculation and treatment of soybean seeds with 5,6-dihydro-2-methyl-1,4-oxathi-ine-3-carboxanilide (75 ml ha^{-1} a.i.), methyl benzimidazol-2-yl-carbamate + methanal (30 ml ha^{-1} a.i.), molybdenum 10% + cobalt 1% + zinc 1% (75 ml ha^{-1} a.i.), and fipronil + thiophanate-methyl + pyraclostrobin (50 g ha^{-1} a.i.), soybean was sown at a density of 35 seeds m^{-2} with 0.45 m between rows. Black oat was sown in rows with 45 kg ha^{-1} of seeds, while ryegrass originated annually from natural reseeding. Fertilizers were applied to both soybean and pastures annually. In areas with inoculated soybean, phosphorus and potassium were applied both before and after establishment to achieve a goal of 4 t ha^{-1} of grain yield. In the pasture phase, 45 kg N ha^{-1} of urea was applied 40 days after pasture was sown (Table 2), with the objective of developing between 4 and 7 t ha^{-1} of dry matter (DM).

Treatments and experimental design

Soybean was planted in five treatments. Cropping system only (CS) was defined as a non-grazed area, whereas ICLS consisted of four sward management heights of 10 (G-10), 20 (G-20), 30 (G-30) and 40 cm (G-40) using put-and-take stocking. This method consisted of using three tester animals per experimental unit (permanent) and a variable animal number with periodic adjustment in an attempt to maintain desired sward height[18]. Sward height was measured at 100 randomized points in paddocks every 15 days using a sward stick[19].

The experimental design was randomized blocks with three replicates, totaling 22 ha. The experimental unit areas ranged from 0.8 to 3.6 ha, according to treatments. Grazing start date generally occurred in July (Table 2) and was defined as the time when herbage mass reached 1500 kg ha^{-1} of DM. Animals used in the pasture phase were crossbreed steers that were approximately 10 months old and averaged 210 kg initial live weight. The strategy for the grazing period was for steers to graze until early November of each year, then steers were weighed [final live weight (LW)], and hauled to a commercial packing plant, where they were slaughtered for meat production.

Management of crop and livestock

Soybean yield (kg DM ha^{-1}) was determined at the R8 stage (harvest maturity) according to phenology scale developed by Fehr et al.[20]. All plants from six samples of 2 m of rows in each paddock were collected. Plant samples were air-dried, and grain was threshed and weighed.

To evaluate livestock production with ICLS under different grazing intensities, average daily gain (ADG, kg d^{-1}) and gain per hectare (GPH, kg ha^{-1}) were calculated. The ADG was obtained by measuring the difference between the initial and the final individual LW of three tester animals throughout the grazing period.

Table 1. Rainfall and mean air temperature recorded near the experiment (2001–2012).

Month	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Study mean	55-yr mean
								Rainfall (mm)						
Jan	240	149	77	246	33	196	95	79	93	555	99	57	160	116
Feb	86	67	213	55	42	8	228	152	110	223	190	101	123	119
Mar	80	144	121	60	218	82	125	71	59	32	165	58	101	115
Apr	248	160	184	171	58	27	42	112	14	125	128	52	110	113
May	40	170	30	148	177	186	162	102	123	113	60	49	113	102
Jun	84	112	185	125	38	93	177	192	71	107	123	NE	119	117
Jul	88	213	148	120	66	87	187	37	66	209	227	NE	132	105
Aug	40	107	70	47	182	122	155	99	195	25	136	NE	107	121
Sep	121	276	100	129	145	87	217	38	273	346	46	NE	162	138
Oct	42	415	195	106	315	59	210	374	84	49	123	NE	179	135
Nov	45	174	198	147	85	116	112	85	439	59	45	NE	137	112
Dec	15	198	370	46	39	165	95	38	173	146	15	NE	118	107
Total	1129	2185	1891	1402	1400	1231	1805	1380	1702	1989	1358	NE	1588	1400
								Mean air temperature (°C)						
Jan	22.6	27.8	24.0	23.9	24.9	26.8	23.5	24.3	22.8	24.0	25.1	24.4	24.5	23.7
Feb	27.3	24.5	23.3	22.3	23.9	25.4	22.1	23.5	24.0	25.0	23.6	26.0	24.2	23.3
Mar	28.4	28.0	22.1	22.7	23.2	24.3	24.4	22.4	23.1	23.3	22.0	23.0	23.9	22.0
Apr	22.1	25.5	19.1	21.4	19.2	20.5	26.6	19.3	21.2	19.5	20.3	19.4	21.2	19.1
May	15.9	21.9	16.5	14.8	17.7	15.6	14.7	15.6	17.7	15.8	15.8	17.9	16.7	15.8
Jun	16.1	17.0	16.0	15.1	17.0	17.0	16.0	12.8	12.0	14.6	12.9	NE	15.1	13.7
Jul	15.9	16.0	13.8	11.8	13.6	16.4	11.4	16.0	11.5	13.3	13.2	NE	13.9	13.6
Aug	19.4	17.0	13.1	14.0	16.6	12.5	13.1	15.1	15.6	14.1	14.2	NE	15.0	14.4
Sep	18.2	16.3	16.3	16.7	13.9	16.1	18.7	14.6	15.8	16.5	16.3	NE	16.3	16.1
Oct	23.1	19.9	19.8	17.7	18.5	19.8	19.9	18.6	18.2	19.3	19.4	NE	19.5	18.4
Nov	23.7	21.3	21.3	19.3	21.9	21.4	20.2	22.1	24.2	20.7	21.8	NE	21.6	20.7
Dec	24.6	22.6	21.5	22.4	22.1	23.7	23.8	23.3	23.9	22.9	22.5	NE	23.0	22.6
Mean	21.4	21.5	18.9	18.5	19.4	19.9	19.5	19.0	19.2	19.1	18.9	NE	19.6	18.6

NE, not evaluated.

The GPH was obtained by multiplying the ADG by the number of animals per hectare each day.

Economic data and analysis

Monthly soybean prices (R$ 60 kg^{-1}) and live cattle prices (R$ kg^{-1}) in Rio Grande do Sul during May 2001 through May 2012 were obtained from the Management Planning Division (Rio Grande do Sul Emater/Ascar). Prices of inputs and operations were obtained from market places in Rio Grande do Sul. For crop inputs, the price survey was collected in November of each year, while May was used for harvesting. For livestock inputs, all values were collected in May. All information was converted into constant R$. Domestic price series were converted from current prices in R$ into constant R$ using the General Price Index (averaged across Brazil cities and all items, from Fundação Getúlio Vargas). To compare the values in US$ the long-term average conversion was made using current R$/US$ exchange rates (daily averages by month obtained from the Central Bank of Brazil/BACEN).

Economic performance was assessed from the five treatments on the basis of gross margin, which is widely used in economics to estimate the production potential of a farm[4,21]. This represents the net revenue (excluding fixed costs) at the farm level[22]. In both phases, gross margin per hectare was calculated as follows:

$$\text{Overall gross margin} = \sum \text{yearly products} - \sum \text{yearly costs},$$

$$\sum \text{yearly products} = \sum \text{crop products} \times (\text{soybean grains sales}) + \sum \text{livestock products} \times (\text{animal sales}),$$

$$\sum \text{yearly costs} = \sum \text{crop operating costs (desiccant} + \text{soybean seed} + \text{sowing} + \text{fertilizer} + \text{herbicide} + \text{fungicide} + \text{insecticide} + \text{application} + \text{harvesting}) + \sum \text{livestock operating costs (black oat seed} + \text{sowing} + \text{fertilizer} + \text{animal purchase} + \text{parasite control} + \text{application} + \text{holding cattle}).$$

Table 2. ICLS dates from the experiment in Rio Grande do Sul, Brazil.

ICLS period	Pasture sowing date[1]	Start grazing date	Finish grazing date	Grazing duration (days)	Soybean planting date	Soybean harvest date	Soybean growth duration (days)
2001/2002	18 May	24 Jul	05 Nov	104	10 Dec	06 May	147
2002/2003	13 May	16 Jul	13 Nov	120	17 Dec	01 May	135
2003/2004	19 May	21 Jul	07 Nov	109	NA	NA	NA
2004/2005	10 May	12 Jul	14 Nov	125	05 Dec	30 Apr	146
2005/2006	04 May	05 Jul	13 Nov	131	02 Dec	05 May	154
2006/2007	11 May	29 Jun	08 Nov	132	15 Dec	12 May	148
2007/2008	12 May	14 Jul	09 Nov	118	18 Dec	17 May	151
2008/2009	17 May	17 Jul	15 Nov	121	NA	NA	NA
2009/2010	17 May	17 Jul	30 Oct	105	17 Dec	17 Apr	121
2010/2011	30 Apr	06 Jul	02 Nov	119	27 Nov	26 Mar	119
2011/2012	19 Apr	10 Jun	07 Nov	150	16 Nov	16 Apr	152
Mean	08 May	09 Jul	08 Nov	121	09 Dec	28 Apr	141

NA, not available.
[1] The sowing date of black oat. Ryegrass originated from natural reseeding.

Crop, livestock and economic data in percentage terms

Mean values over the study period were calculated for ADG, GPH, soybean yield and gross margin. Mean values for each treatment were then transformed into percent deviation from the overall mean.

Statistical analysis

Analysis of variance was performed using mixed models (SAS Institute Inc., Cary, NC) with fixed effects for sward management, years (repeated measurements) and the interaction between sward management and year and random effects for blocks (paddocks). When differences between means were detected, treatments were compared using Tukey's HSD test at a significance level of 5%. Pearson correlation analysis was performed between climate data during crop development (December to April) and soybean yield ($P<0.05$).

Results

Total annual rainfall and its distribution varied greatly during the experimental period in comparison to the long-term average. The long-term mean annual rainfall was 1400 mm (55 years) and the study mean was 1588 mm, with a peak between September and October in both periods (Table 1). Two extreme years were 2010, with the greatest rainfall during the summer, and 2012, with the lowest rainfall. March was the driest month during the study period, with an average of 101 mm of rainfall, ranging from 32 (2010) to 218 mm (2005). The minimum and maximum average monthly temperatures during the experimental period were 13.9 and 24.5°C in July and January, respectively.

Crop phase

No difference ($P>0.05$) was observed in soybean yield between cropping system only and ICLS, nor among grazing intensities ($2516 \pm 103\,kg\,ha^{-1}$). There was also no interaction between sward management and experimental years ($P>0.05$). Soybean yield was affected by experimental years ($P<0.001$; Fig. 1), where higher values were observed in 2002/2003 ($3738 \pm 82\,kg\,ha^{-1}$), 2006/2007 ($3586 \pm 82\,kg\,ha^{-1}$) and 2009/2010 ($3417 \pm 85\,kg\,ha^{-1}$) and smallest value in 2011/2012 ($311 \pm 82\,kg\,ha^{-1}$). Variation in soybean yield was positively correlated with rainfall ($r=0.82$; $P<0.001$).

Livestock phase

The variables of ADG and GPH showed interactions between sward management and experimental year ($P<0.001$; Table 3). The interaction for ADG was mainly due to no differences among treatments in 2001, 2002, 2005, 2007, 2008 and 2009, and lower ADG with lower sward heights in 2003, 2004, 2006, 2010 and 2011. Considering the mean values from the study period, ADG was lower when pasture was managed at 10 cm in comparison to sward heights between 20 and 40 cm. The interaction for GPH represented a difference in magnitude of treatment effects among years, in which the strongest decline of GPH with increasing sward height occurred in 2001, 2005 and 2009. In the mean of the study period, with increasing sward heights, a gradual reduction in GPH was observed ($P<0.05$). Treatment G-10 was the least stable during the 11 years of the study, ranging between 0.663 and 1.072 $kg\,day^{-1}$ and between 314 and 612 $kg\,LW\,ha^{-1}$ for ADG and GPH, respectively. Treatment G-20 had intermediate variation, while treatments G-30 and G-40 were most stable, presenting similar values for ADG and GPH among years.

Table 3. ADG and GPH in the long-term ICLS experiment in Rio Grande do Sul, Brazil.

ICLS period	Average daily gain (kg day^{-1})*				Gain per hectare (kg LW ha^{-1})*			
	Sward management							
	G-10	G-20	G-30	G-40	G-10	G-20	G-30	G-40
2001	0.89ABa	1.03ABa	1.11Aa	1.09Aa	480ABa	311Cb	231Abc	121Ac
2002	0.92ABa	1.22Aa	1.19Aa	1.07Aa	541ABa	537Aa	301Ab	154Ab
2003	0.73Bb	1.01ABab	1.14Aa	1.12Aa	540ABa	440ABCa	268Ab	153Ab
2004	0.73Bb	1.14ABa	1.24Aa	1.21Aa	530ABa	490ABa	321Ab	202Ab
2005	0.96ABa	1.24Aa	1.13Aa	1.10Aa	515ABa	385ABCab	288Abc	167Ac
2006	0.76ABb	1.05ABab	1.08Aab	1.15Aa	612Aa	496ABa	328Ab	175Ab
2007	0.69Ba	1.02ABa	0.95Aa	1.00Aa	428BCa	501ABa	356Aa	185Ab
2008	0.74Ba	0.94ABa	0.97Aa	0.92Aa	495ABa	419ABCa	233Ab	156Ab
2009	0.83ABa	0.89Ba	0.96Aa	1.10Aa	529ABa	390ABCab	337Abc	178Ac
2010	0.66Bb	1.01ABab	1.17Aa	1.15Aa	314Cab	375ABCa	318Aab	175Ab
2011	1.07Aab	0.82Bb	1.21Aab	1.23Aa	459ABCa	343BCab	324Aab	230Ab
Mean ± SE	0.82 ± 0.03b	1.03 ± 0.03a	1.10 ± 0.02a	1.10 ± 0.02a	495 ± 15.6a	426 ± 14.8b	300 ± 10.1c	172 ± 6.2d

Values followed by different upper-case letters in the column and lower-case in letters the row differ significantly according to the Tukey test ($P < 0.05$). *($P < 0.001$) for interaction treatment × year. Grazing at 10 cm (G-10), grazing at 20 cm (G-20), grazing at 30 cm (G-30), grazing at 40 cm (G-40).

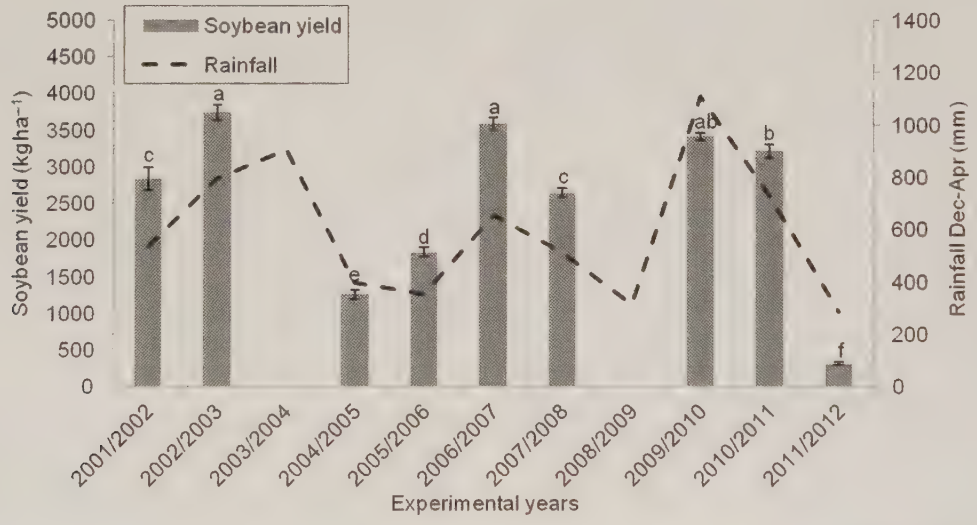

Figure 1. Soybean yield (kg ha^{-1}) and rainfall from December to April in long-term ICLS experiment in Rio Grande do Sul, Brazil.

Economic data

An interaction ($P < 0.001$) between treatments and experimental years was observed for gross margin (Table 4). There was great variability in gross margin during the study period, with higher values observed in 2002/2003, 2006/2007 and 2007/2008 and smaller values in 2004/2005, 2005/2006 and 2011/2012 (Table 4).

Considering means of the study period (Table 5), gross margin was lower in CS than ICLS ($P < 0.05$). When comparing grazing intensities, greater gross margin was observed in G-10 and G-20 than in G-30 and G-40 ($P < 0.05$). During the crop phase there were no differences in any of the economic factors among treatments. Treatment G-10 had the greatest overall operating cost per ha due to livestock operating costs ($P < 0.05$), whereas CS had the lowest overall operating cost. Regarding revenue, overall and livestock phases showed similar behavior. Livestock gross margin was superior in treatments G-10 and G-20.

Variations in treatments relative to overall mean

In percentage terms, all treatments were similar for soybean yield (Fig. 2). For GPH, treatments G-10 and G-20 had values superior to the overall mean of the long-term experiment. For ADG, treatment G-10 was inferior

Table 4. Gross margin in the long-term ICLS experiment in Rio Grande do Sul, Brazil.

ICLS period	Gross margin (Brazilian real ha^{-1})*				
	Treatment				
	G-10	G-20	G-30	G-40	CS
2001/2002	1677BCDa	1021CDEa	1354ABa	1056Aa	NA
2002/2003	2985Aab	3053Aa	2214Aab	2217Aab	1910Ab
2003/2004	NA	NA	NA	NA	NA
2004/2005	987CDEa	318DEab	−28Cab	−154Cb	−298Bb
2005/2006	623DEa	135Ea	262BCa	112BCa	−203Ba
2006/2007	2050ABCa	2119ABa	1697Aa	1621Aa	1219Aa
2007/2008	2568Aba	2451ABa	2084Aab	1948Aab	1288Ab
2008/2009	NA	NA	NA	NA	NA
2009/2010	1770BCDa	1952BCa	2095Aa	1575Aa	1146Aa
2010/2011	1418BCDa	1568BCDa	1740Aa	1958Aa	1460Aa
2011/2012	222Eab	826DEa	−117Cab	−145BCab	−434Bb

Values followed by different upper-case letters in the column and lower-case letters in the row differ significantly according to the Tukey test ($P < 0.05$). * ($P = 0.007$) for interaction treatment × year. 1 US$ = 2.27 Brazilian real. Grazing at 10 cm (G-10), grazing at 20 cm (G-20), grazing at 30 cm (G-30), grazing at 40 cm (G-40) and CS (cropping system only). NA, not available.

Table 5. Economic analysis in the long-term ICLS experiment in Rio Grande do Sul, Brazil.

	Financial data (Brazilian real ha^{-1})				
	Treatment				
	G-10	G-20	G-30	G-40	CS
Overall operating costs	4916a (158)	3898b (108)	3037c (89)	2276d (59)	1325e (54)
Crop operating costs	960a (50)	962a (50)	961a (53)	974a (47)	971a (39)
Livestock operating costs	3956a (126)	2936b (82)	2076c (71)	1301d (41)	354e (16)
Overall gross revenue	6466a (326)	5362b (285)	4268c (250)	3412d (209)	2071e (258)
Crop gross revenue	1953a (201)	1974a (205)	1943a (199)	2102a (209)	2071a (258)
Livestock gross revenue	4519a (186)	3382b (151)	2323c (113)	1306d (59)	–
Overall gross margin	1569a (190)	1518a (202)	1256b (188)	1133b (189)	760c (202)
Crop gross margin	994a (176)	1020a (174)	989a (167)	1135a (182)	1061a (220)
Livestock gross margin	572a (102)	407ab (85)	285b (60)	12c (44)	–

Values followed by different lower-case letters in the row differ significantly according to the Tukey test ($P < 0.05$). 1 US$ = 2.27 Brazilian real. Grazing at 10 cm (G-10), grazing at 20 cm (G-20), grazing at 30 cm (G-30), grazing at 40 cm (G-40) and CS (cropping system only).

and the other treatments were similar to the overall mean of the experiment. Gross margin was superior to the mean of the long-term experiment in treatment G-10 and inferior in CS.

Discussion

Long-term grazing intensities did not influence soybean yield responses, contradicting the paradigm that grazing animals negatively impact soybean yield[23]. Use of no-till with constant presence of plants (soybean and pasture) promotes the stability of soil physical properties. Another study performed in this area showed that changes in soil physical properties observed in areas grazed at different sward heights and in the non-grazed area did not influence soybean establishment and yield[24]. In a study from Illinois[7], trampling and soil disturbance from cattle on cropland had no negative effect on subsequent corn yields and may have helped increase yield over continuous corn plots. A similar analysis found that winter grazing on corn residues had minimal effect on subsequent soybean yield[25].

Stability of soybean yield between sward management practices may be related to soybean reproductive plasticity and harvest index stability in response to variations in shoot biomass[26]. During soybean growth, rainfall and its distribution varied greatly over the period of this study (Table 1), and variation in annual soybean yield was associated with rainfall (Fig. 1). Similarly, in the

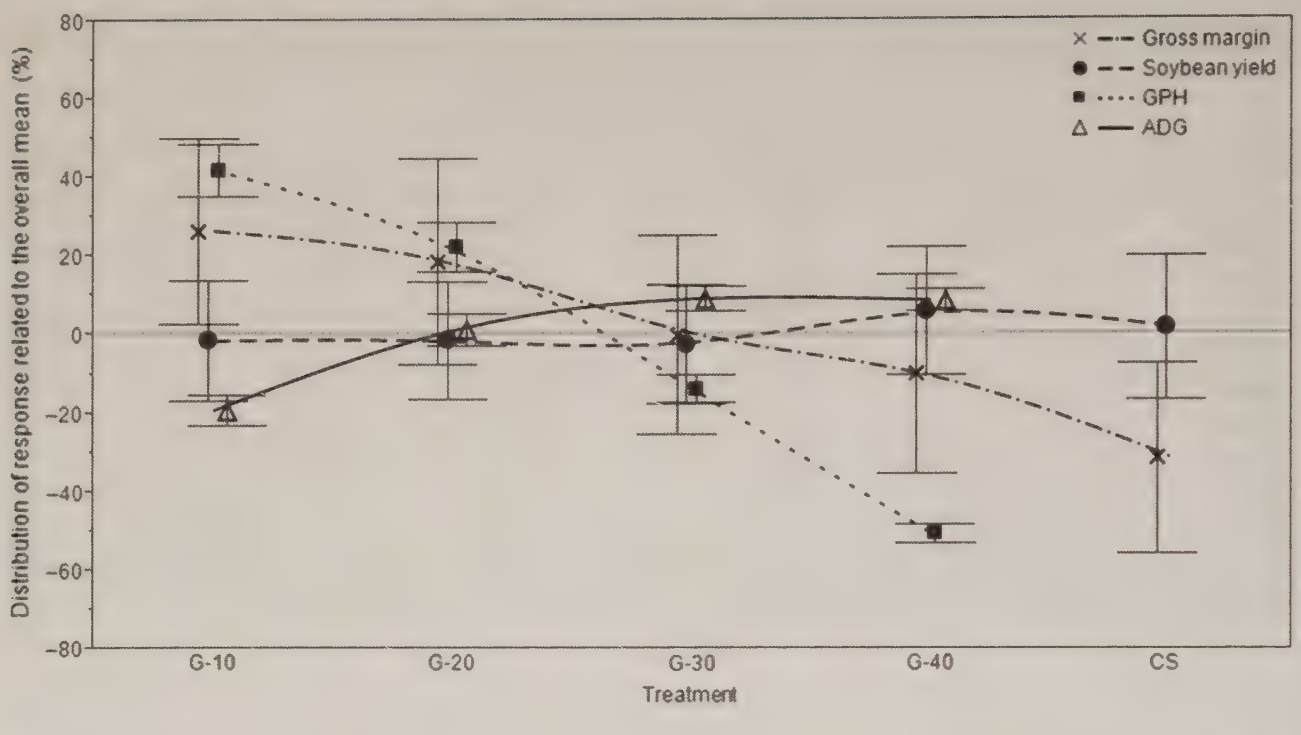

Figure 2. Influence of treatments from the overall mean (%) of gross margin, soybean yield, GPH and ADG in a long-term experiment of ICLS in Rio Grande do Sul, Brazil. Grazing at 10 cm (G-10), grazing at 20 cm (G-20), grazing at 30 cm (G-30), grazing at 40 cm (G-40) and CS (cropping system only).

main soya growing area of Argentina, soybean yield exhibited high inter-annual variation, with differences of 2000 kg ha^{-1} or more[27].

Considering livestock production, the negative relationship between ADG and stocking rate is well established[28]. Therefore, decisions concerning grazing intensity are especially important because of the close relationship between ADG and animal production per hectare[29]. When increasing grazing intensity, ADG is normally reduced, but greater beef production per unit land area is observed[30,31]. From an initial average LW of 210 kg and considering the grazing duration for each ICLS period (Table 2), G-10 had the lowest final LW (309 ± 5 kg), with increasing weights for G-20, G-30 and G-40 (average of 340 ± 5 kg). Considering the whole ICLS, it should be noted that low sward heights result in lower forage mass and therefore lower amounts of residual DM for no-till management[32]. In the other extreme, increasing sward height increases stem components and total biomass, with consequent reductions in green forage mass and nutrition value[33]. Animals can achieve greater ADG in high swards; however, GPH is significantly reduced (Table 3).

Profit is an important factor in decision making about land use, even in perception of long-term related to specific alternative practices[34]. Generally, farmers seek land use and land management to maximize profits, subject to resource constraints and subject to factors beyond their control, including input costs[22].

Land-use decision making might consider revenue from differences in yields and the probability that crop/livestock yields will be higher than specialized systems. Independent of sward height management, gross margin was greater in ICLS than cropping system only. Comparing years with rainfall during crop development (December to April) above (2002/03; 2006/07; 2009/10; 2010/11) and below (2004/05; 2005/06; 2007/08; 2011/12) the study mean (Table 1), there was a greater difference observed in gross margin between sward height treatments and CS in years with lower rainfall. Gross margin in CS was negative in three of those four years. In years with higher rainfall, gross margin in CS was positive, but still only 72 ± 11% of that in ICLS. The presence of the livestock phase was important to avoid economic loss in years with low rainfall, but important also in wet years to increase economic gain.

Mixed crop–livestock systems also generate higher economic efficiency in saving production costs through complementarities between crop and livestock[35]. The CS treatment had an operating cost with cover crop establishment (Table 5) for soil and water conservation. Therefore, ICLS may be considered a strategy to improve economic performance and promote conservation practices[36]. As for production, the combination of crops and livestock produces more food than either separately from the same area[37].

In this long-term experiment, gross margin was optimized for G-10 and G-20 treatments (Table 5),

which could be considered heavy and moderate stocking rates, respectively. In Wyoming, the most profitable stocking rate in years with favorable prices was between moderate and heavy, but in years with average or unfavorable prices, the optimum stocking rate was moderate or slightly lower[38]. Environmental risks and costs increase with intensification, as does the level of disturbance and utilization of grasslands, leading to loss of soil resources which increases costs of replacing nutrients and species and in managing nutrient runoff[39].

Finally, aiming to reduce the economic dependence on single crops and specialized systems by considering grazing management in ICLS, a balance between economic and production outcomes for the system as a whole was achieved with a sward management strategy between treatments G-10 and G-20.

Conclusion

The ICLS investigated was an effective option for diversifying the soybean-cropping system. This long-term research addresses the positive influence of sward management on average daily gain, GPH and gross margin, while showing no effect on soybean yield. The optimal grazing intensity to achieve production and economic goals for this ICLS was reached at 10–20 cm sward height.

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From a conceptual framework to an operational approach for managing grassland functional diversity to obtain targeted ecosystem services: Case studies from French mountains

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Abstract

Research to understand and manage ecosystems to supply services has recently spurred a functional view of their biodiversity. In particular, approaches based on functional traits rather than species diversity are increasingly used to reflect interactions between organisms and their environment. These approaches bring a functional perspective to the study of community structure responses to disturbances and resources, and of their effects on ecosystem functioning and services. From an academic perspective, we propose a conceptual framework based on species functional traits to better infer how grassland management practices (fertilization, defoliation regime) along with abiotic factors influence plant, animal and microbial community composition and a range of services in grassland ecosystems. The core of the framework relies on combinations of plant functional traits and associated microbial features that specifically respond to environmental and management factors and influence ecosystem services. To overcome stakeholders' difficulty in applying the concept of functional traits, we propose an operational approach implying the mapping of plant communities distributed into five plant functional types (PFTs). The approach was used for fields in grassland-based livestock farms from two French grassland networks. We evaluated its ability to predict a range of services including forage provision and non-market services according to environmental and management drivers. PFT-based plant community composition predicted forage services reasonably well but responded weakly to environmental gradients. To cope with the observed limitations of current predictive approaches, we suggest including soil microbial functional types and adaptive management rather than using a prescriptive scheme.

Key words: cutting, fertility gradient, grass species, grazing, plant functional type, soil food web

Introduction

Increased energy costs, climate change, biodiversity losses, fluctuation of selling prices and greater concerns for environmentally friendly production are among the emerging factors that make agricultural competitiveness much harder to achieve and maintain. Unlike the rather stable context of the past decades, farmers and their advisors must now strive for a dynamic competitive advantage that requires rethinking land use to meet environmental and socio-economic challenges. Main challenges in this context are reducing negative externalities of agriculture (e.g., greenhouse gas emissions) without decreasing agricultural production and financial returns, and whenever possible increasing non-market services [e.g., cultural value, carbon (C) sequestration, erosion prevention, etc.]. Grasslands can provide a range of services[1]. For farmers, grasslands primarily provide feedstuffs for

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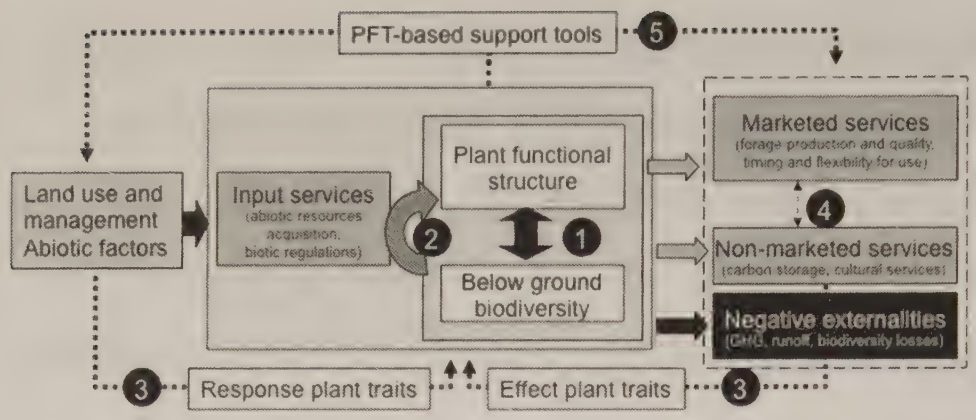

Figure 1. Ecosystem services and negative externalities potentially delivered by grasslands. Input services contribute to biological, physical and chemical processes supporting agriculture. Marketed services contribute to agricultural productivity, whereas non-marketed services do not (yet) directly contribute to agricultural income (except in specific cases such as agro-tourism farms); PFT, plant functional type; numbers (1,...,5) rely on key relations that are explained in the text; full arrows, biophysical relationships; dotted arrows, relationships based upon plant traits.

herds in grassland-based livestock systems and input services (e.g., maintenance of soil fertility; biological regulations) when they are introduced in crop rotations in mixed crop–livestock systems[2]. For other stakeholders such as environmental agencies and policy makers, grasslands contribute many non-marketed services. Farming, previously dedicated mainly to food production, is likely to change with an increasing recognition of grassland multifunctionality[3]. Since land use and associated land cover and management intensity influence the range of services provided by grassland biodiversity, incentives such as subsidies and regulations should promote a widening of farmers' objectives, i.e., producing forage along with delivering a range of services by managing biodiversity at different scales[4]. Two scientific challenges arise for meeting these aims. First, it is necessary to quantify the levels at which services provided by grassland agro-ecosystems are delivered and to predict them according to management and abiotic factors. Secondly, for the sake of operationality, research outputs must be translated into user-friendly tools for stakeholders, especially the farmers.

Evaluating and predicting services provided by grassland agro-ecosystems have recently progressed using an approach based on identifying the role of functional diversity. Trait distribution of the community is a consequence of environmental filters caused by either biotic or abiotic factors (e.g., land use and management) that determines ecosystem processes such as biogeochemical cycling and ecosystem productivity[5]. These processes explain the supply of services, e.g., primary production explains forage supply that can be potentially predicted by combinations of traits[6,7]. Ecosystem functioning is indeed the end result of the operation of multiple filters on a hierarchy of scales, which, by assembling individuals with appropriate responses, results in communities with varying trait compositions[8]. Ecosystem processes and services are shaped through land use and management, directly by farmers and indirectly by institutions through norms, subsidies and advice. Thus, ecosystem-based learning or decision supports based on species-trait approaches can be developed into a framework and has been recently proposed[9]. However, two main issues still need to be addressed.

First, this cascade of relations renders prediction of ecosystem services difficult. The environmental factors affecting trait distribution interact in a complex manner between management drivers such as synthetic and organic fertilizers, grassland use (date, intensity and frequency of defoliation), local climate and edaphic conditions, and legacy of previous use that can differentially act on traits related to different processes. Furthermore, relations between species functional composition and biotic and abiotic factors or ecosystem services are complex: a given trait can respond differently to several drivers, several traits may be needed to scale-up to each ecosystem process and each service may be related to a suite of processes that depend on different combinations of traits[10]. Above- and below-ground components of grassland ecosystems are also strongly linked through a variety of both direct and indirect interactions that operate across trophic levels[11–13] (Fig. 1, arrow 1). Our first objective, aiming to better understand and predict biodiversity-dependent services, was thus to propose a framework that integrates these linkages between above-ground and below-ground diversity, especially for the acquisition and retention of resources provided by functional diversity (Fig. 1, arrow 2). We aimed to build a parsimonious framework to infer grassland services based on a limited number of plant functional traits. We selected key plant traits among those responding to management and environmental factors and having major effects on processes modulating processes related to ecosystem services. For simplicity, we focused on above-ground diversity, whose role has been intensively documented during the

past decade, assuming that it can be also a proxy for below-ground diversity (Fig. 1, arrow 3). Finally, we assessed whether this integrated framework can help to determine tradeoffs between services, given that optimum management is stakeholder- and scale-dependent (Fig. 1, arrow 4).

The second issue to be addressed is related to the fact that a trait-based approach is rarely implemented by the intended end-users, especially farm advisors, and is not well-tailored for enhancing the learning process in a management perspective[14]. Trait-based agro-ecosystem models and indicators used to represent and understand grassland ecosystem functioning are not necessarily salient for end-users, i.e., they are often not perceived as relevant by decision makers[15]. Thus, our second objective was to propose an operational approach to infer multiple-service delivery by grasslands. It is based on broad plant groups organized into functional types defined by a suite of plant traits, which is better adapted to support learning and monitoring by farm advisors. The ability of the approach to assess grassland ecosystem services by characterizing plant communities and determining tradeoffs and synergies among services (Fig. 1, arrow 5) were evaluated. Then, considering the uncertainties of both simplifications [relying only on plant functional diversity and considering plant functional types (PFTs) instead of plant traits] and the context of environmental and management uncertainties, we suggest ways to apply and supplement this approach for guiding grassland management.

To reach these two goals, we first reviewed the literature to examine how characterizing plant growth strategies and functional traits can help understand the link between management practices and forage production or other services; we also examined to what extent above-ground biodiversity and below-ground biodiversity are linked. Next, we designed an integrated framework that summarizes the impacts of environmental and management factors on processes related to ecosystem services by characterizing plant strategies of resource use and growth. We then proposed an operational approach for building relevant support tools for end-users to infer grassland services based on a few PFTs. Finally, we evaluated this operational approach for assessing plant community responses to management and effects on services and examined how to implement this approach through support tools for assessing ecosystem services and guiding management practices.

Species-trait-based Approaches for Bridging Species Responses to Management, Environment, and Ecosystem Properties and Services: State-of-the-art

Currently, the importance of functional components of biodiversity has been described for plants[8,9]; invertebrates[16]; microorganisms[7,16]; meso- and macrofauna[15,17]; vertebrates[18]; along with relations between these trophic levels[19]. We focused on the following main components of grasslands: plants and key species involved in the soil food web (earthworms, nematodes, bacteria and fungi).

Characterizing plant-growth strategies to link management practices to primary production and forage services

Many studies have reported that a main dimension of plant functioning and/or specialization is related to resource acquisition and use[20,21], which leads to distinguish acquisitive versus conservative plant types. This is related to a continuous variation in leaf traits, from thin, N-rich, short-lived leaves with high photosynthetic rates, to thicker, more fibrous, N-poor, longer-lived leaves with lower photosynthetic rates. Leaf traits such as specific leaf area, leaf nitrogen content and leaf dry matter content of water-saturated leaves are descriptors of these plant-growth strategies, which perform well for predicting species location on an axis of resource capture, usage and availability[22]. A second axis of specialization is usually related to plant height, which captures plant competitive ability [e.g., the leaf-height-seed (LHS) model[23]] and some aspects of plant reproductive strategy. Plant height is a key proxy to account for competition for light[23] and is positively related to root depth, another trait involved in competitive ability for water[24]. The timing of height growth is also of particular relevance to assess resource acquisition and partitioning among interacting species, leading some authors to define the second dimension of growth strategy as growth–height trajectories, in relation to flowering phenology, i.e., early versus late[25].

Species' functional-trait syndromes, i.e., suites of traits, are the outcome of their evolutionary response to selection pressures from habitat characteristics[26]. Assuming that these characteristics result from the legacy of land-use, edaphic and climate conditions, we hypothesized that plants develop similar strategies above and below ground[27–31]. Recent studies have shown correlations between morphological root traits and growth strategies defined on the basis of leaves. For example, greater specific root lengths, proportions of biomass of fine roots and root N concentration were found in fast-growing species[32]. This suggests a substantial capacity for nutrient uptake and assimilation[29], low water transport capacity[30] and fast root turnover[33]. Such trait sets may be attributable to species living in nutrient-rich habitats, allowing rapid organ turnover and growth. In contrast, high root tissue density and large diameter were characteristic of plants exhibiting a long root-lifespan[34,35] and living in nutrient-poor habitats. More recent studies[22,31] have shown correlations between leaf and root traits, revealing similar above- and below-ground plant strategies

modulated by drought-tolerance capacity of species. Moreover, patterns of root traits, including decomposition rate, mirrored those of leaf traits, resulting in a similar species clustering. The highly correlated variation in root and leaf traits and potential decomposition rate also suggests that changes in functional composition of communities in response to anthropogenic changes should strongly affect biogeochemical cycles at the ecosystem level[36].

High nutrient availability favors plant species with an acquisitive strategy and/or tall stature[8], since competitive exclusion removes non-competitive species. In contrast, low nutrient availability favors conservative, stress-tolerant species, especially when facilitation exists[37]. However, significant relations are expected between plant community functional structure and other environmental gradients such as climate constraints or water stress that may involve other combinations of traits. Moreover, functional traits related to plant phenology respond to defoliation but also to resource availability[38]. Intermediate stress, however, favors the coexistence of both plant strategies for cutting as well as for grazing[39]. During the reproductive phase, canopy height before cutting or grazing best describes the effect of defoliation intensity and frequency upon plant functional composition[38].

Community functional structure is usually defined by two components: community-level weighted mean (CWM) of trait values and functional divergence (FDg) indices[8,40]. The CWM calculation is based on the 'mass-ratio' hypothesis, which assumes that the extent to which the traits of a species affect ecosystem properties depends on the abundance of the species in the community[41]. FDg describes the dissimilarity in traits among individuals (species) coexisting within a community[42]. Large values are often related to functional complementarity between species[43]. Understanding diversity effects on ecosystem functioning usually occurs by partitioning plant diversity into two processes: selection versus complementarity[44]. The former, assessed via CWM, occurs when plant species with particular traits dominate ecosystem processes [e.g., most of species having low or high leaf dry matter content (LDMC)], whereas the latter, assessed via FDg, results from better resource use due to trait differences (coexistence of species having low and high plant trait values). Such an effect is expected under intermediate levels of fertility[16,45] and disturbance. Complementarity can occur among grasses and legumes, and among grass functional types with differing traits in relation to the timing, location and rate of resource use.

Convergent results among several studies show the relevance of the plant-trait approach for successfully evaluating forage provision by permanent grasslands[46,47]. More generally, it was shown that traits such as leaf dry matter content associated with response to nutrient gradients strongly overlapped with those determining net primary production[6]. The same trends were found for tissue composition[48]: PFTs with an acquisitive strategy have a low lignin and cellulose content. Furthermore, high FDg leads to a flatter growth curve, allowing flexibility in harvest date because one can vary the harvest date without greatly changing herbage yield or its quality[48]. In addition, the balance between plant groups differing in their phenology (grass *versus* dicotyledonous species) allows the capture of more light over the growing season[49].

Above-ground—below-ground biodiversity linkages: toward management of below-ground biodiversity

The rhizosphere is the interface between soils and plants[50], i.e., a place where biotic interactions are intense between plants and soil microorganisms. Most processes associated with above- and below-ground interactions in ecosystems occur in this relatively limited soil volume, which is directly influenced by root exudates and functioning[11]. Interactions also occur via above-ground litter inputs and decomposition and foliage-induced changes in soil microclimate. It has been shown that the diversity, abundance and/or functioning of soil microorganisms, in particular rhizospheric ones, can strongly depend on plant species or functional group[51–54]. As feedback, soil micro-organisms play a fundamental role in the biogeochemical cycling of inorganic and organic P[55] and N[56] and consequently availability of these resources to plants. Thus, they ultimately affect plant functional composition[11]. In the context of our approach, the functional characteristics of rhizospheric microbial communities can thus be viewed as 'extended functional traits' of plant species. In a recent study, it was demonstrated that plant traits can be a powerful tool for understanding the mechanisms behind plant–soil interactions and ecosystem functioning and for predicting how changes in plant–species composition associated with global change will feed back into the soil system[13]. Associated microbial functional traits can have affinity for C or N substrates or maximum substrate use rate, as demonstrated for soil nitrite oxidizers along an N gradient[57].

The multiple processes involved in plant–soil interactions largely determine the cycling of C via the forms of soil organic matter, from labile to recalcitrant, and nutrients, mainly N and P, which benefit ecosystem functioning. Accounting for soil microbial functional traits increasingly appears necessary to infer soil functioning[7] and delivery of services properly, and to adequately define appropriate management practices[13,58,59]. For instance, symbiotic and free-living biological N fixation represents a sustainable N input into N-poor agrosystems[60]. In addition, the balance between N mineralization, nitrification and denitrification determines, in relation with plants' preference for N forms, soil fertility and potential N losses from the ecosystem[61]. Thus, future agricultural practices should increasingly consider managing soil biota to enhance the delivery of a range of ecosystem services and to improve the resilience of

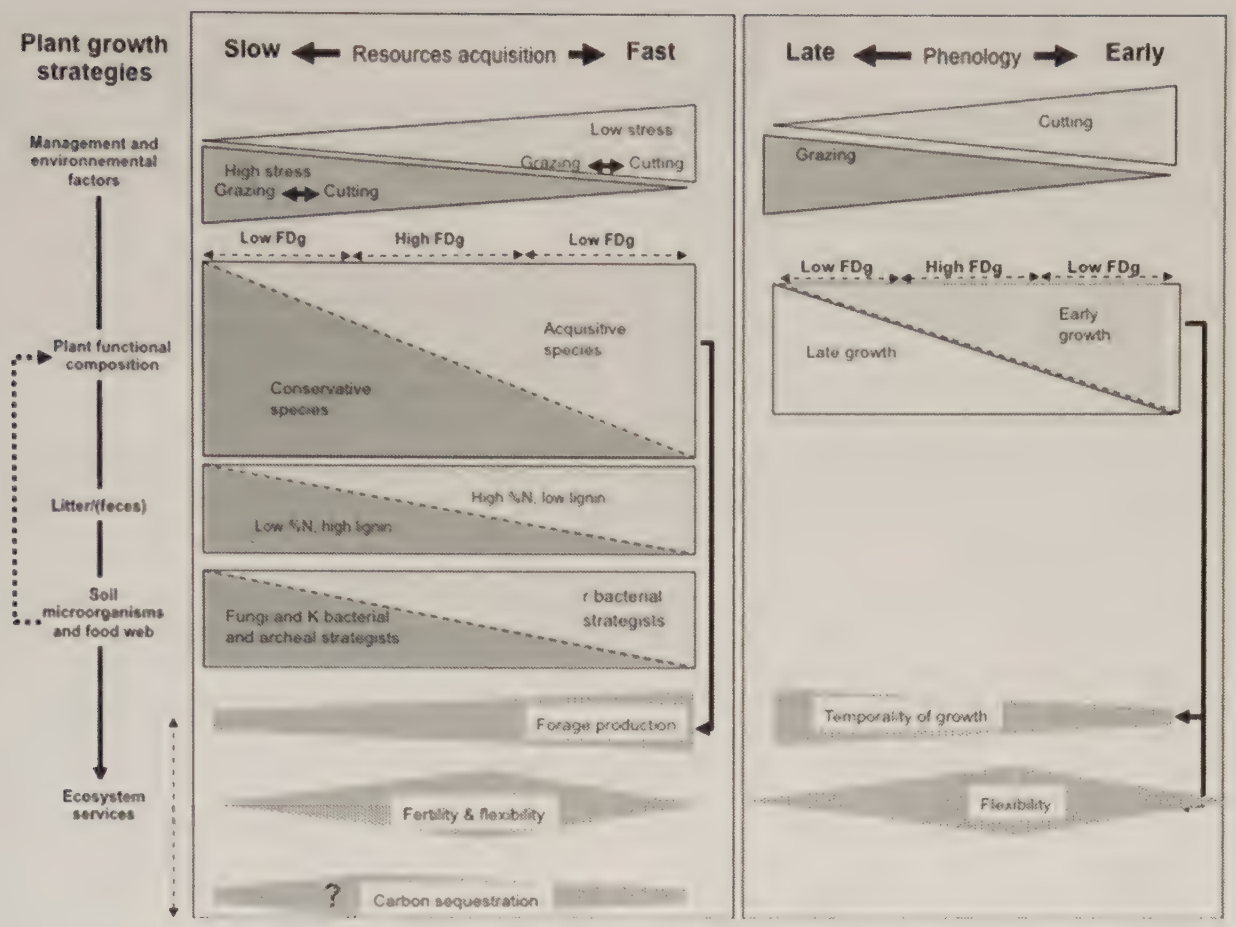

Figure 2. For two main axes of plant-growth strategies (left and right), the figure displays the relationships between (from top to bottom): management-induced stresses and disturbances; plant-community functional divergence (FDg); litter composition; soil microbial community and food web composition (from[11]); and several ecosystem services (forage production, soil fertility, flexibility for management and C sequestration); the height of the triangle or trapezium along the *X*-axis reflects the value of the criterion considered.

agricultural systems. For instance, it was demonstrated that soil arbuscular mycorrhizal fungi communities from different agricultural fields vary in their impact on plant productivity and nutrient-leaching losses[62]. Similarly, inoculation of plant-growth promoting rhizobacteria, such as *Azospirillum* strains, is currently being tested to increase crop yields[63]. This paves the way for agricultural practices that will try to directly or indirectly manage soil organisms, even microorganisms, and their functional traits in the future.

An Integrated Framework and Operational Approach for Managing Grasslands

A trait-based framework to infer services delivered by grasslands

For managed grasslands, plant traits include key effect traits that can be used to predict services because they integrate the effect of a large range of ecological processes, including those occurring below ground. For the resource-use dimension, fast versus slow growth plant types display differences in their ability to capture and use resources due to differences in root-system architecture[64], quality of litter[65], rhizospheric processes[66] and periods when resources are required (e.g., differing minimum-temperature thresholds for growth[58]). Low stress *vis-à-vis* resource availability (nutrients or water availability) favors acquisitive species. In this context, nutrient cycling is driven mainly by bacterial *r*-strategists with a high activity rate and a low affinity for substrates[57,67]. This supports rapid, leaky nutrient cycles and low net accumulation C in soil. These drivers and associated soil processes lead to high forage production and quality at the leafy stage. In contrast, high resource-related stress, up to a certain extent, leads to slow nutrient cycling and promotes soil C sequestration[68]. Intermediate levels of fertility allow different plant types to coexist, which allows overyielding due to complementary effects that reduce competition (input service)[69] and provides great flexibility in harvest or grazing dates[48] (Fig. 2, left side). Disturbances may reduce or amplify the effect of stress. For given climate and soil conditions, mowing promotes

species with an acquisitive strategy, whereas grazing promotes species with a conservative strategy. However, the magnitude of these effects depends on grazing intensity[69]. High grazing intensity favors the return to the soil of material with a C:N ratio lower than that of litter. In contrast, low grazing intensity increases the quantity of litter with approximately twice the C:N ratio of that of green plant tissue. The level of stress and disturbance required to maximize fertility and C sequestration is not well known[70]. Nevertheless, the level of stress and disturbance that maximizes each service is likely to depend on the service considered[71]. Defoliation regime is probably the main driver of plant-community composition for the timing of herbage growth, e.g., the time at which peak herbage occurs during regrowth (Fig. 2, right side). Coexistence within a community of late and early plant strategies smoothes the herbage growth pattern[48] and may help optimize light capture.

Previous versions of this framework have been used for teaching students and training experts involved in advising farmers[14]. The current version of this framework can be extended to investigate plant traits associated with a stress factor or to identify functional groups of populations exhibiting similar responses to it (e.g., drought survival[72]). More specifically, it can be used as a first step to qualitatively design custom communities for desired ecosystem services based on hypotheses of plant functioning in species assemblages[64]. However, complementary work should be done to design an operational approach that can be used by farmer advisors.

A salient operational approach for managing grassland agro-ecosystems

From plant traits to PFTs. Although popular and successful in scientific arenas (e.g.,[73]), the plant-trait approach rarely prevails in non-scientific circles, even when delivering quantitative relations between land use, plant community composition and ecosystem processes and services. Although the approach works, stakeholder feedback shows that it is not relevant in practice because it is too time-consuming, and trait values such as LDMC and specific leaf area (SLA) are too abstract for end-users[14]. To address the approach's relevance to decision makers' needs[74], we made two changes to the characterization of grassland vegetation compared with the framework presented above. First, we classified species into functional types (i.e., groups of species sharing the same collection of attributes[75]). We adopted five grass functional types (GFTs) covering the diversity observed in species growing in the same environmental conditions in France based on six plant traits (LDMC, SLA, flowering date, leaf lifespan, leaf tensile strength, plant height)[76] (Appendix 1). These five GFTs were characterized by traits reflecting the two major growth strategies (flowering date to distinguish late versus early growth; LDMC to distinguish fast versus slow growth) (Fig. 3). We also

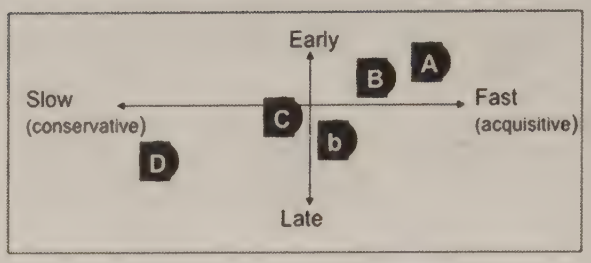

Figure 3. Mapping of five grass functional types (A, B, b, D, C) by two plant traits (leaf dry matter content, flowering date) representing two plant-growth strategies, fast versus slow, early versus late, respectively.

verified that GFTs were consistently ranked according to herbage growth, i.e., slope and intercept of growth decreased (Appendix 2). Second, we focused on grass species because they have more similar plant-trait values[77] and properties[48] than dicotyledonous species coexisting in grassland communities. Consequently, we consider dicotyledonous species as a whole for estimating their overall impact on plant-community properties according to their percentage in the plant community[48]. On this basis, the response of plant-community structure to management and environmental factors and its effect upon forage provision can be analyzed via GFT assemblages to develop a generic and low-input method for farm advisors[78]. Thus, plant community structure can be characterized by:

- the percentage of grass species in the vegetation cover (G)
- the percentage of each of the five GFTs (*pi*)
- a diversity index, *S*, characterizing the evenness of GFT percentage and richness, calculated as a Simpson index: $S = 1 - \sum_{i=1}^{n} p_i^2$; it is an indicator of plant-strategy specialization within a plant community. Based on the analysis of 1378 plant communities from a range of temperate grasslands in France, the relative abundances of the different GFTs within plant communities are unimodal[79] and can be considered as an FDg index.

Such plant community characterization via PFTs has been recently extended to perennial tropical areas, where C3 and C4 species coexist[80], and sown grasslands[64,72].

From PFTs to services. Forage production and quality can be assessed by the percentage of species having a fast growth strategy[79] because these types are composed of species with low LDMC (Table 1). Based on the framework proposed (Fig. 2), we assumed that the same was true for C sequestration. Furthermore, based on findings showing the existence of contrasted plant preferences for the different chemical forms of N (ammonium versus nitrate)[11,12], we hypothesized that, in low soil N availability conditions, the coexistence of species having different growth strategies can allow higher N uptake in comparison to plant community composed only of plants with a conservative growth strategy.

Flexibility in management allowed by the timing of herbage growth can be assessed by the proportion of GFT

Table 1. Indicators used for characterizing grassland properties and services.

Service	Component	Indicators of grassland properties	Indicators of grassland services
Forage production management	Production	GFT_{fast} (%)	Herbage yield; stocking rate
	Quality	GFT_{fast} (%)	Herbage digestibility
	Flexibility allowed by timing of herbage growth	GFT_{late} (%)	Herbage growth pattern over the growing season; date of peak herbage; spreading of harvest dates
	Flexibility allowed by diversity	*S*	Shape of growth curve around peak herbage
Input	Fertility permitted by coexistence of plant types having acquisitive and conservative strategies	*S*	N uptake/N fertilizer supplied
Non-marketed	C sequestration	GFT_{fast} (%)	Soil C content; C:N ratio soil and plant

GFT_{fast}, grass functional types having a fast growth strategy; functional diversity index.

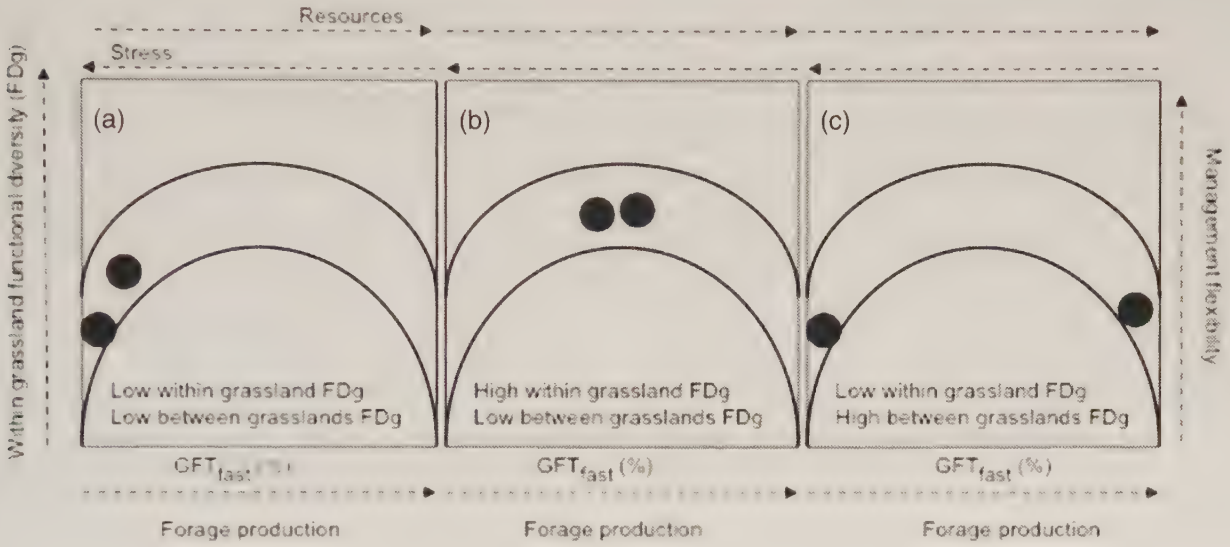

Figure 4. Relationship between functional divergence (FDg: within grassland functional diversity on *Y*-axis) and between grassland functional diversity (FDv on *X*-axis, assessed through the percentage of grass functional types having a fast growth strategy: GFT_{fast}) coupling with effects (forage production and management flexibility on *X*- and *Y*-axis, respectively) and drivers (resource availability and stress intensity on top of *X*-axis). Lines represent the enveloping curves, and circles illustrate three main patterns (a–c) considering two grasslands or sets of grasslands.

with a late growth strategy, which is related to late flowering dates (GFT_{late}). The flexibility allowed by within-plant-community diversity can be assessed by *S*, assuming that the more numerous these GFTs are, the flatter the growth curve around peak herbage is, as found using LDMC[48], because these communities are a mixture of GFTs with early and late flowering dates and short and long leaf lifespan.

The $GFT_{fast} \times S$ operational approach to characterize within- and between-grassland functional diversity. To propose an operational way to infer grassland responses to management and environmental drivers and their effects on ecosystem services, we considered the resource dimension of plant-growth strategy, represented by the percentage of GFT_{fast} (instead of LDMC in the trait-based framework initially presented) and the *S* index for GFT diversity (instead of the FDg index for LDMC) (Fig. 4). As constructed, the relation between the *S* index and the percentage of GFT_{fast} is parabolic, with maximum FDg expected for mean values of GFT_{fast} and minimum FDg expected for low and high values. Three main patterns are possible according to the combination of scale and level of FDg (Fig. 4). However, there is large uncertainty, because when $GFT_{fast} = 100\%$, *S* can theoretically vary from 0 (one GFT) to 0.5 (two GFTs with the same percentage).

Case Studies

Objectives and data

Case studies were used to evaluate the operational approach proposed, examining relations between plant

Table 2. Description of the two case studies used to test the framework.

Location	Central Pyrenees	Aubrac
Latitude/longitude	42°50N 1°17E	44°37N 2°59E
Area of sampling	about 1 × 2 km	20 × 40 km
Grass species in pasture biomass (%) (SD)	60.0 (14)	70.4 (20)
Soil pH (0–5 cm) (SD)	5.88 (0.41)	5.84 (0.41)
Annual temperature (°C) (altitude)[1]	10.8 (1000 m)	10.1 (860 m)
Annual rainfall (mm)	1014	1284
Annual potential evapotranspiration (mm)	1200	816
Range of altitude of the plots (m asl)	615–1200	800–1400
Number of farms studied	4 beef	4 beef and 4 dairy
Plant species richness (n)	239	176
Biomass or proxy	Spring growth curve (and shape): $n = 18$ spring and summer growth curve: $n = 6$	Stocking rate (8 farms 3 land-use types)
Plant analysis	C and N at herbage peak ($n = 18$)	
Soil analysis	C and N ($n = 18$)	C and N ($n = 16$)

[1] Climate data are averages over the past 10 years.
m asl, meters above sea level; SD, standard deviation.

functional composition and either environmental and management variables, or ecosystem services. Most of these relations were previously established considering a single plant trait[38,39,48,76,77]: LDMC, which reflects well on the resource-use dimension and weakly on the reproductive pattern of plant-growth strategies. We re-examined these relations to evaluate whether considering the two dimensions of plant-growth strategy performed well and whether considering pre-established PFTs instead of plant traits provided similar results.

The study was based on the data from two mountainous regions in France (Table 2) dominated by unsown species-rich grasslands used for feeding cows (grazing and hay). In these regions of sufficient precipitation, temperature is the main climate characteristic affecting plant productivity. Farm surveys were performed to record management practices, such as three defoliation regimes: cutting, grazing then cutting, and grazing only. Surveys were supplemented by calculation of Ellenberg indicator values (EIVs) for nutrients (N), soil reactivity (R) and moisture (M)[81]. EIVs reflect the relation between each species and environmental factors, and management practices. The strengths of EIVs are that they integrate species behavior over several years[82]. Plant and soil analyses were also performed to verify the consistency between expectations of the framework and observations for leaf tissue composition (e.g., cellulose) and C:N ratio.

Evaluating the approach

From PFT composition to ecosystem services. We verified that the percentage of GFT_{fast} was a proxy for estimating forage production, herbage digestibility and several key variables of nutrient cycles. For example, it was significantly and positively correlated with spring herbage growth rate measured at the field level (network 1, Fig. 5a) as well as with stocking rate calculated for a set of fields at an annual scale (network 2, not shown, $n = 24$; $r^2 = 0.78$). GFT_{fast} was also positively correlated with herbage growth rate measured in spring (Fig. 6a). In contrast, it was significantly and negatively correlated with plant and soil C:N ratios, the slope and intercept being greater for plants than for soil (network 1, Fig. 5b).

The *S* index being a proxy of within-field FDg, we examined its influence on temporal dynamics of grassland forage biomass. The shape of the growth curve around peak herbage was flattened when the *S* index was high (Fig. 6a). Indeed, a mixture of contrasting GFTs smoothed the growth curve because they have different leaf lifespans and flowering times (see Fig. 6b for network 1). In addition, we found that for less fertilized grazed grasslands (N supplied = $24.4 \pm 26\ kg\ ha^{-1}$), N uptake was significantly and positively correlated with *S* ($r = 0.4$; $P < 0.05$; $n = 38$; network 2). Including soil pH and moisture with EIVs increased the correlation ($r = 0.66$; $P < 0.001$). We also verified that the percentage of GFT_{late} was a proxy for evaluating timing of herbage growth within and among growing cycles. For the first growth cycle, the higher the percentage of GFT_{late}, the later the date at which peak herbage occurred (Fig. 6b). However, the greater its percentage, the higher the herbage biomass ratio was between the second and first harvests performed in summer and in spring, respectively ($r = 0.93$; $P < 0.01$) (Table 3, network 1).

Plant-community composition response to environmental and management factors. ANOVA of GFT_{fast} percentage was calculated to compare the three defoliation regimes and two regions, with field altitude and applied N fertilizer as covariables. We found a significant effect of region ($P < 0.01$) and defoliation regime ($P < 0.05$); GFT_{fast} percentages were 58, 60 and 68% for cut, grazed then cut, and grazed grasslands, respectively. Effects of field altitude and applied N fertilizer were also significant ($P < 0.01$ and 0.1, respectively).

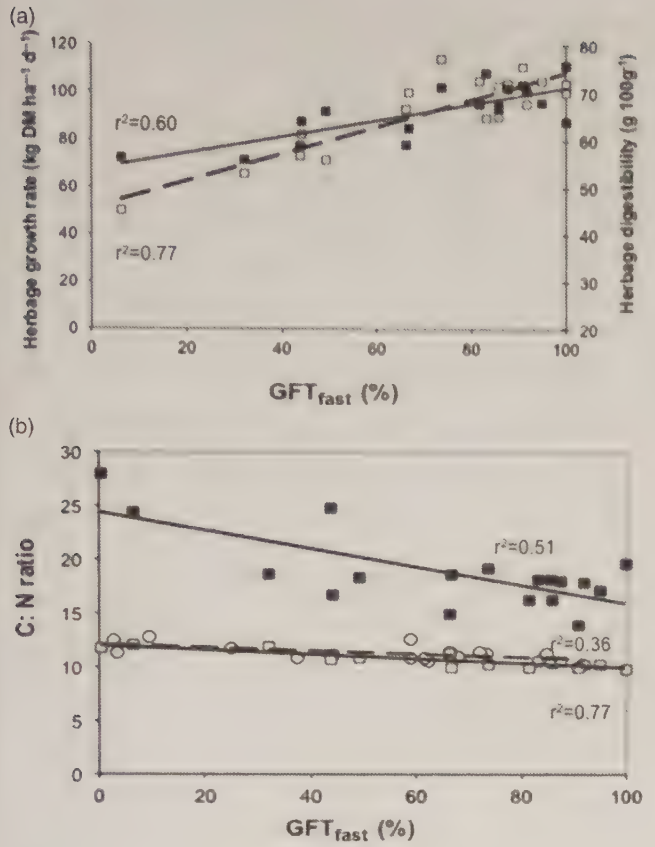

Figure 5. Relations between indicators of services (*Y*-axis) and the percentage of grass functional types having a fast growth strategy: GFT_{fast} at the land-management-unit level. (a) Herbage growth rate (closed symbols) and plant digestibility (open symbols) for the first growing cycle (grassland network 1). (b) C:N ratios for plants (closed symbols) and soil (open symbols); squares for grassland network 1, circles for grassland network 2.

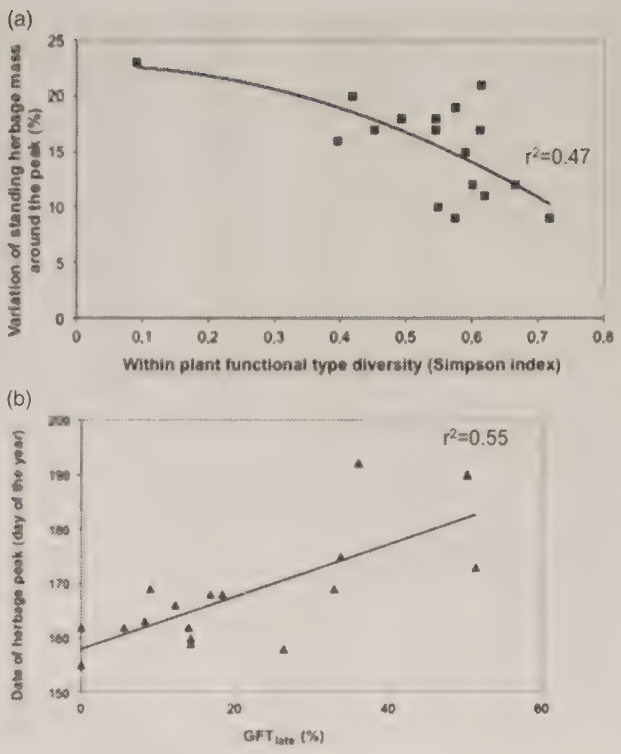

Figure 6. Herbage features related to plant functional-type composition. (a) Shape of the growth curve (±20 days around peak herbage) according to an index of grass functional-type (GFT) diversity ($P<0.05$ when the extreme value was not considered). (b) Date (Julian days) at which peak herbage occurred according to the percentage of grass functional types having a late growth strategy: GFT_{late}. The date at which the herbage peak occurred was significantly and positively correlated with GFT_{late}.

Correlations between the GFT_{fast} percentages and raw data describing management and environmental factors were weak (Table 4). Including Ellenberg indicator values for nutrient and soil reactivity (pH) created more generic results (no effect of region) and resulted in higher correlations (Table 4). The direction of effects for temperature N (or N-EIV) and R-EIV were consistent with those expected. To test the hypothesis that FDg indices depended on levels of stress and disturbance (Fig. 4), we calculated linear regressions between each *S* and environmental (altitude, temperature and region) and management factors separately for percentage of $GFT_{fast}<45\%$ or >45%. For network 2, we found significant effects ($P<0.001$): positive for N fertilization and negative for field altitude for $GFT_{fast}<45\%$, and the opposite sign for both variables when $GFT_{fast}>45\%$. However, this relation was not found for network 1. Therefore, this result, at least partly, validates the hypothesis that the coexistence of plants with different growth strategies captures more N.

Support tools for assessing ecosystem services from PFTs. Moving from the integrated framework to the operational approach requires shifting from the study of practices as factors for understanding agro-ecosystem functioning to mechanisms for managing multiple services in a given context, given environmental and data uncertainties. To illustrate this change, we portrayed typical grassland functional compositions using ascendant hierarchical clustering. As an example, we defined seven types of data from networks 1 and 2 (Fig. 7a). Forage services

Table 3. Late grass growth strategy (type b in percentage) and herbage yield ($t\,ha^{-1}$) at first and second harvests for six grasslands of network 1.

Grassland	GFT_{late} (%)	Harvest 1 (H1)	Harvest 2 (H2)	Ratio (H2: H1)
1	5	4.7	4.0	0.85
2	22	3.6	3.5	0.97
3	7	3.1	3.2	1.03
4	20	2.1	2.6	1.24
5	52	2.1	4.1	1.95
6	23	2.8	4.0	1.43

GFT_{late}, grass functional types having a late growth strategy.

Table 4. Regression analyses between the percentage of grass functional types having a fast growth strategy and environmental and management variables [e.g., Ellenberg indicator variables (EIV), *R* = soil reactivity, N = nutrients] considering raw variables or proxies of processes describing them.

		Environmental factors				Management factors			
Management		**Region**	**Altitude**	**Temperature**	**R-EIV**	**N applied**	**N-EIV**	r^2	**SE**[2]
Cutting (+grazed)	With raw variables	−17.5***[1]	−0.05**	/	/	0.07*		0.36***	17
	With proxy of processes	/	/	8.4***	6.5***	/	9.4***	0.57***	14
Grazing	With raw variables	−13.2*	ns			Ns	/	0.046*	21
	With proxy of processes	/	/	4.4**	8.4**	/	16.2***	0.44***	15

Regressions were calculated separately for cut and grazed grasslands considering the two grassland networks together. $^{**}P<0.01$; $^{***}P<0.001$.
[1] Regression coefficient for each variable.
[2] Standard error.
/: means not considered in the regression analysis.

Table 5. Characterization of the seven grassland vegetation types for four features.

Grassland vegetation type	Herbage growth index (maximum = 1)	Flowering date (degree-days)	Plant digestibility at leafy stage ($g\,kg^{-1}$)	Diversity index (maximum = 0.8)
1	0.93	831	831	0.32
2	0.87	856	823	0.60
3	0.78	921	810	0.67
4	0.75	890	808	0.70
5	0.69	942	804	0.73
6	0.65	848	791	0.48
7	0.50	1027	766	0.48

for each vegetation type can be assessed using previously established relations[83]. Vegetation types 1 and 7 have high and low herbage growth and digestibility as well as early and late flowering time, respectively; however, they have low functional diversity (Table 5). Vegetation types 3, 4 and 5 have the highest plant functional diversities but intermediate values for herbage growth and digestibility. Flowering time for vegetation type 6 is early, whereas herbage growth and digestibility are low. Other services can be assessed qualitatively using the framework (Fig. 4). Stakeholders may use these results confidently because species plant traits [leaf live span (LLS), tissue composition] used for defining functional types are ranked in the same order, regardless of the growing conditions[84]. Furthermore, plant community functional composition correlates well with services, at least herbage production and digestibility ($r^2>0.6$). Applying the $GFT_{fast} \times S$ framework (Fig. 4) to field data (Fig. 7b) portrays grassland at different scales (field, farm, region, etc.) by calculating the percentage of each vegetation type.

As found elsewhere (e.g.,[85]), relations between grassland functional composition and management or environmental factors are usually weak. Fundamentally, PFT provides 'average effects' that fail to provide managers with the information they need to address site-specific conditions, as found for other issues[86]. Thus, relations for predicting effects of plant composition on some components of the soil food web, such as decomposer communities, are context-dependent[11]. In addition, replacing plant traits by PFT decreases the accuracy of estimates of the relation between plant functional composition and management and environmental factors.

Toward a trial-and-error method to cope with uncertainty. Uncertainty complicates management of grasslands to obtain specific ecosystem services. The main issues are (i) which management practices are relevant for changing a given service (as seen in the case study) and (ii) which PFTs should be associated in sown grasslands when considering the services desired. The integrated framework (Fig. 2) provides an overview of combined effects of climate and management practices. Modeling relations between plant functional composition and management practices in case studies provides only weak indications (Table 4 and Fig. 4). Therefore, to cope with these uncertainties, we suggest that farm advisors use an adaptive-management approach supported by research outcomes, such as that presented in this paper. Once plant-community composition is portrayed (e.g., by the $GFT_{fast} \times S$ framework) and effects of environmental and management variables are roughly predicted to frame the action (e.g., using statistical models developed between plant community structure and management factors), it consists of a trial-and-error process based on monitoring plant functional structure to adjust management according to local soil and climate characteristics. Management practices can be viewed as 'experimental treatments' that

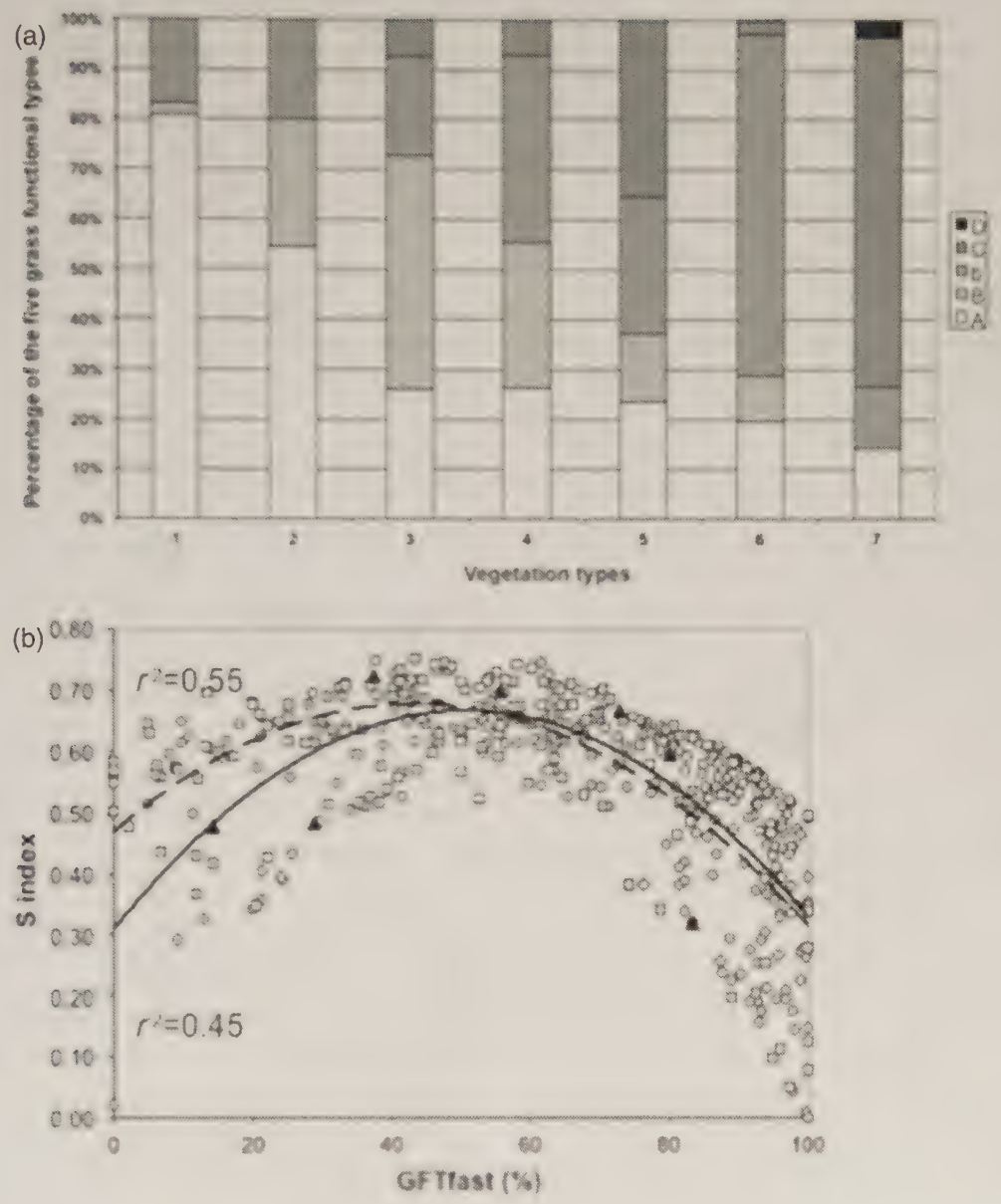

Figure 7. Support of relations between services and management and environmental factors; example based on 415 fields located in two regions. (a) Percentage of the five grassland functional types (GFTs) of seven assemblage types, ranked according to decreasing percentage of grass functional types having a fast growth strategy (GFT_{fast}) established from cluster analysis. (b) Observed distribution of mean functional divergence (*S* index) as a function of percentages of GFT_{fast} for Aubrac (squares) and Ercé (circles); triangles are for mean percentages of the seven assemblage types.

are implemented according to the management design. Learning could occur by monitoring plant functional structure, even though changes in soil biota functional structure can require several years to occur, as shown after changes in grassland management[87] and in conservation agriculture[88].

Conclusion

Based on the analysis of plant-growth strategies influenced by resources and phenology, coupled with a review of above-ground–below-ground biodiversity linkages, we have shown that plant traits and associated soil microbial community and food web composition can be aggregated into an integrated framework. It shows how plant traits shape a large set of services provided by grassland agroecosystems (forage and management services, fertility, and magnitude of C sequestration) and how they respond to land use and management practices. To put this framework into practice, we developed an operational approach based on PFTs and showed how support tools can be built from it. We have shown that restricting grassland characterization to above-ground plant traits for simplicity and choosing PFTs in a management perspective lead to uncertainty in predicting

Table A1. ANOVA of the five grass functional types for LDMC and flowering time.

Grass functional types	LDMC		Flowering time		
	Significance	Growth strategy	Significance	Growth strategy	Example of species
A	a	Fast	a	Early	*Holcus lanatus* L.; *Lolium perenne* L.
B	ab	Fast	b	Early	*Arrhenatherum elatius* L., *Dactylis glomerata* L.
b	bc	Slow	c	Late	*Agrostis capillaris* L., *Phleum pratense* L.
C	c	Slow	b	Early	*Briza media* L., *Festuca rubra* L.
D	d	Slow	c	Late	*Deschampsia cespitosa* L., *Molinia coerulea* L.

Data having a different letter in the same column were significantly different at the 5% level.

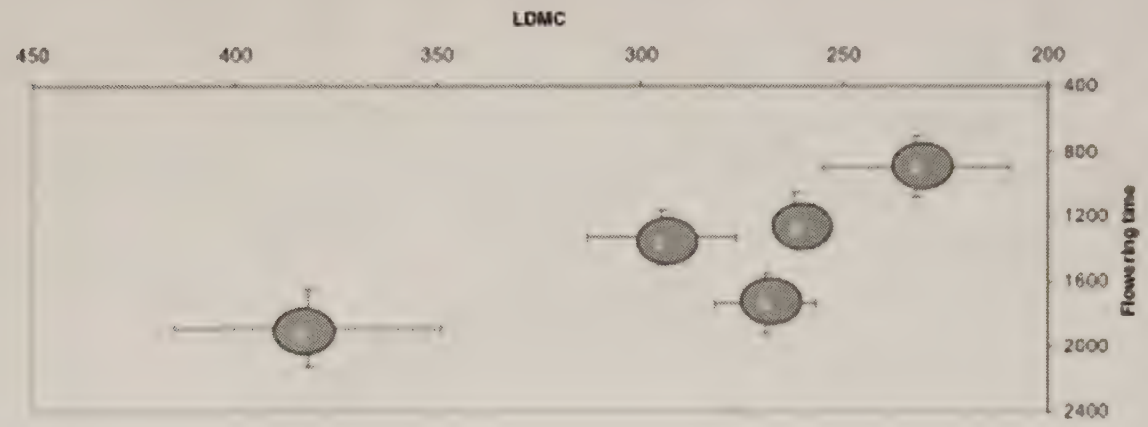

Figure A1. Ranking grass functional type according to decreasing LDMC (leaf dry matter content in mg g^{-1}) and flowering time in degree-days (°C) values; bars on the figure are standard deviations.

services from management practices and environmental factors alone. To cope with this uncertainty, we suggested a trial-and-error approach.

To generalize the approach, relations between drivers and ecosystem services should be established across scales[89], e.g., exploiting within- and among-site environmental heterogeneity of soil, climate and management. Additional sound relations between these drivers and ecosystem services can be expected. On the other hand, the applicability of the integrated framework and operational approach to sown grasslands must be evaluated in more depth. They can be used to define which species should be associated in mixtures according to the services targeted (e.g., to increase grazing season length or soil fertility) and to monitor plant-community composition to adjust defoliation management across seasons or years.

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Appendix 1

Characterization of five pre-established grass functional types (GFT: A, B, b, C, D) for leaf dry matter content and flowering time (Table A1, Figure A1); analysis was done for the 30 most currently observed perennial grass species in France[79] among the 38 studied by Cruz[76].

Table A2. Comparison of slope and intercept of the relationship between W and day of year for the five GFTs.

Source	df	*F*	*P*
Day of year	1	309.77	0.0000
Intercept	4	7.37	0.0001
Slope	4	2.68	0.0438

Table A3. Regression coefficients.

GFT	Intercept	Slope
A	−1088	16.2
B	−763	11.8
b	−692	11.4
C	−652	10.5
D	−451	7.7

Appendix 2

Analysis of spring growth of grass species ($n = 15$) growing in a pure stand (Tables A2 and A3); for each species;

sward was cut at two, three or four times at different places for measuring standing herbage mass (W), (number of data = 55); after[90].

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Solar desalination for sustainable brackish water management in arid land agriculture

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Abstract

An agricultural facility aimed at sustainable production of crops in arid environments was built and tested in Hatzeva, Israel. The facility relies on solar-powered desalination with nanofiltration membranes to treat the local brackish water (EC = 2.32 dS m^{-1}) and produce high-quality irrigation water (EC = 0.71 dS m^{-1}). Red beet, a salt-tolerant crop, was grown with the concentrate stream (EC = 4.73 dS m^{-1}), eliminating the need for concentrate disposal and with potential net economic benefits. Agricultural experiments with variable irrigation water quality, application rate, and four staple crops (potato, maize, millet and sorghum) were conducted over two growing seasons between September 2010 and June 2011. The desalination plant operated at low pressure (4.3 bar) and energy consumption (1.37 kWh m^{-3}) and with little maintenance over the entire study period. The results of the agricultural experiments consistently showed that irrigation with desalinated water promoted more efficient use of resources such as water and inorganic fertilizers. A reduction of 25% in the irrigation rate and use of fertilizers compared with best-practice guidelines was achieved with desalinated water, with no detectable detrimental effect on the marketable yield. On the contrary, a statistically significant yield increase was observed for sorghum (+10%). An increase in water productivity with desalinated water was observed for all four staple crops.

Key words: arid agriculture, brackish water agriculture, desalination, nanofiltration membranes, renewable energy

Introduction

The rising food demand brought on by growing world population and competition for natural resources between economic sectors compels future agricultural systems to increase production per unit area and reduce losses of production capacity due to land and water degradation[1]. The link between sustainable water use in agriculture and food security was reaffirmed recently during the 2012 World Water Week in Stockholm (http://www.worldwaterweek.org/). A resource-efficient approach is particularly crucial in areas that already experience overexploitation of scarce freshwater resources and where population growth rates are high. In the Middle East and North Africa (MENA) region, 85% of water use is for irrigation, and the dependency on groundwater aquifers is the highest in the world. The availability of environmentally sound technologies to cope with volatile food prices, high dependence on imports, rural poverty and unemployment is of strategic importance to regional food security and sustainable development[2].

Irrigation in the MENA region and elsewhere increasingly relies on marginal quality sources, such as saline water from brackish aquifers. Although international statistics on the diffusion of brackish water irrigation are lacking, brackish water with EC of 2 dS m^{-1} or higher is used for irrigation to various extents in more than 40 countries[3]. In India, it is estimated that 24% of the annual net groundwater draft consists of saline and/or sodic water, most of which is used for irrigation[4]. Crops cultivated with brackish water worldwide include alfalfa (*Medicago sativa*), sorghum (*Sorghum bicolor*), sugar beet (*Beta vulgaris*), wheat (*Triticum aestivum*), cotton (*Gossypium hirsutum*), date palms (*Phoenix dactylifera*), artichoke (*Cynara cardunculus*), barley (*Hordeum vulgare*) and rye grass (*Lolium* spp.)[5]. Brackish water irrigation is often a consequence of progressively deteriorating water qualities in aquifers due to shrinking natural

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freshwater recharge by precipitation, modifications in the subsurface hydrochemical processes related to over-exploitation, and build up of residue of dissolved substances in the soil after the irrigation water is lost by the crops through evapotranspiration. Some of the world's major food-producing regions are threatened by accelerating rates of saltwater intrusion in coastal aquifers[1].

Brackish water irrigation can be sustained over prolonged periods of time when appropriate soil, crop and irrigation management strategies are implemented. These may involve salt leaching, water drainage, addition of chemical amendments or biological management[6]. However, the lack of proper know-how determines the development of salinity, sodicity, ion-specific toxicity and nutrient imbalances in the soils[7]. Statistics from FAO's Information System on Water and Agriculture (Aquastat, http://www.fao.org/nr/water/aquastat/main/index.stm) indicate that the area equipped for irrigation that has become salinized due to mineral buildup caused by inadequate drainage is higher than 25% of the total area in 14 countries in the MENA region, sub-Saharan Africa, South America and Asia. The area salinized by irrigation in the 51 countries for which such information is available in Aquastat amounts to 363,000 km^2.

Even in the presence of adequate management, brackish water irrigation promotes an inefficient and potentially highly unsustainable use of the available water resources[8]. First, high salinity levels cause osmotic imbalances and reduce water uptake and transpiration, which results in lower yields than obtainable with freshwater irrigation[9]. Second, the choice of crops is limited by the specific salinity tolerance. Third, large volumes of water in excess of plant requirements are necessary to leach salts and limit the potential for damage to plants and soil structure due to salt accumulation[8]. Advancements in agriculture technology aimed at the production of desalinated water for irrigation offer a potentially more resource-efficient and sustainable alternative, particularly in hot, arid regions where renewable solar energy can be exploited to reduce the energy costs and carbon footprint of desalination[10].

This paper presents a first-of-its-kind application of solar-powered membrane desalination to arid agriculture. The main objective of the study is to provide a proof of concept of the technical feasibility of solar membrane desalination at the farm-scale level. To this purpose, we describe and test viable solutions for the minimization of the system's energy requirements, achievement of an ionic composition in the membrane permeate that is suitable for irrigation of four widely grown staple crops (i.e., potato, maize, millet and sorghum), and disposal of the desalination brine by growing a salt-tolerant crop (i.e., red beet). Moreover, we test the hypothesis that irrigation with desalinated water promotes a more efficient use of resources than brackish water irrigation, where use efficiency is measured by the productivity of water, i.e., the ratio between the marketable yield and the irrigation volume. An increased productivity of fertilizers is expected as well, since less water is washed away from the root zone. We present the results of the first year of operation of a pilot unit constructed in Hatzeva, Israel, and the outcome of agricultural experiments performed during two growing cycles in 2010/11.

Material and Methods

Location

The experimental system was constructed at Hatzeva (Lat. 30°28′N, Long. 35°10′E, Alt. −125 m m.s.l.) in the Arava Valley of Israel, south of the Dead Sea. The Arava basin is extremely arid, with average annual precipitation of about 50 mm. Only ephemeral streams run into the valley. Rainstorms are infrequent and limited to a short period in the winter. Economic activities in the region rely heavily on the exploitation of local, brackish aquifers for highly intensive agriculture, and export of off-season horticultural crops to the European markets. Brackish water irrigation with salinities of 2–3.5 $dS\,m^{-1}$ is practiced as a rule. Hatzeva hosts the Yair Experimental Agricultural Research Station of the Central and Northern Arava Research and Development, which is responsible for developing new agricultural technologies and disseminating them among local farmers. The site has high solar irradiation levels, with average daily global radiation ranges between 3000 and 8000 $W\,m^{-2}$ in December and June, respectively.

Solar-powered nanofiltration (NF) desalination unit

A pilot membrane desalination unit was installed at the Yair station in Hatzeva in the autumn of 2009. The unit was designed to desalinate the local brackish water and produce 5 $m^3\,d^{-1}$ of permeate freshwater. A diagram of the proposed design scheme is shown in Fig. 1.

The chemical water quality at the selected well was monitored periodically over a period of 3 years and showed little seasonal variation (see Table 1). The water is characterized by low turbidity (0.15 NTU) and concentration of total suspended solids (2 ppm), total dissolved solids (1577 ppm), and boron (0.34 ppm). The unit is equipped with two Dow Filmtec NF90-4040 NF membranes in one pressure vessel. The advantages of the proposed design with NF membranes *vis-à-vis* reverse osmosis membranes in terms of lower energy consumption and ionic composition of the permeate for the local conditions at Hatzeva are discussed in detail elsewhere[10]. A positive displacement pump with a helical rotor (Grundfos SQFlex 1.2–2) pressurizes the water to the extent required for membrane filtration. The design operation pressure of the membranes and permeate flux of the NF membranes are 5 bar and 16.3 liters $m^{-2}\,h^{-1}$ (lmh), respectively. The design recovery rates for each

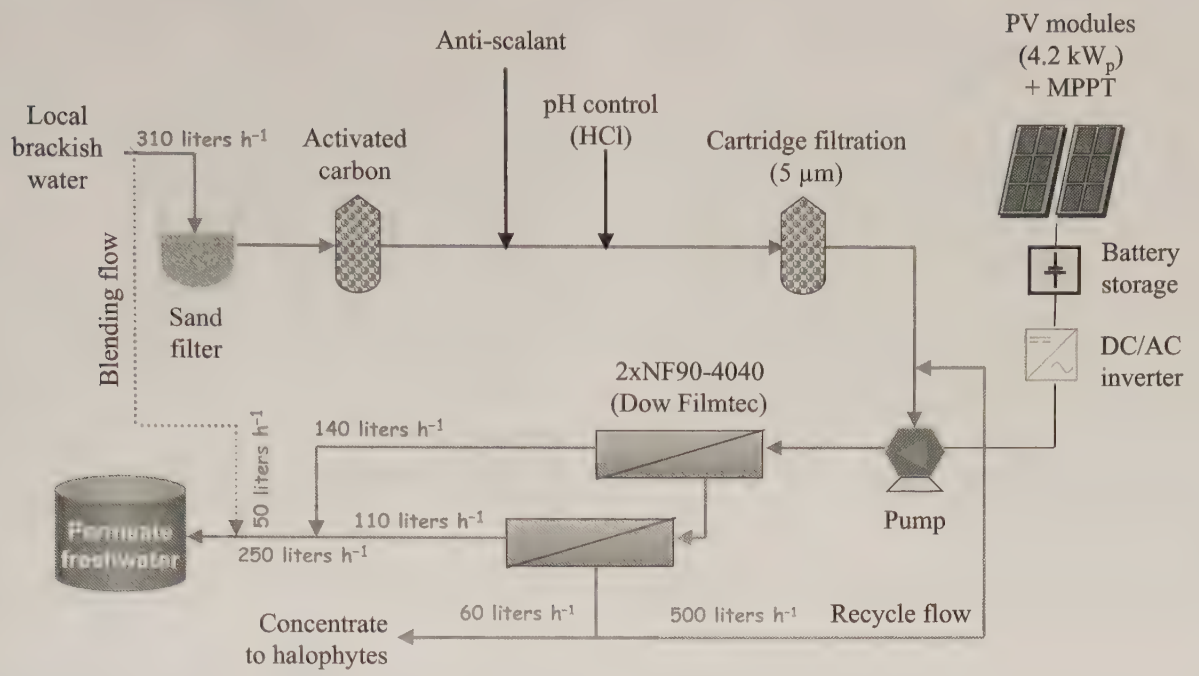

Figure 1. Design scheme of the pilot solar desalination unit at Hatzeva, Israel.

Table 1. Measured electrical conductivity and concentration of selected ions in the brackish feed water, desalinated permeate water after blending, and concentrate during the experimental period (means ± SE, $n = 11–13$).

	Brackish	Desalinated	Concentrate
EC ($dS\,m^{-1}$)	2.32 ± 0.04	0.71 ± 0.05	4.73 ± 0.18
Ca^{2+} (ppm)	181 ± 5	33 ± 2	431 ± 11
Mg^{2+} (ppm)	88 ± 2	17 ± 2	210 ± 4
SO_4^{2-} (ppm)	523 ± 13	99 ± 12	1268 ± 33
Cl^- (ppm)	340 ± 11	120 ± 7	742 ± 24
HCO_3^- (ppm)	233 ± 6	56 ± 4	510 ± 10

membrane are 17 and 16%, respectively. Conventional pre-treatment was installed consisting of sand filtration, micro-filtration with pore size 5 μm, and active carbon cartridge filtration. A recirculation flow was installed, which recycles nearly 90% of the concentrate from the NF membranes back through the membranes ($0.5\,m^3\,h^{-1}$). Although it was designed to achieve a recovery rate of 80%, during the period of operation described here the system was run at a conservative recovery rate of 60% to guarantee smooth operation and minimal maintenance during the agricultural experiments. Antiscalant chemicals and hydrochloric acid were added to inhibit scale formation and for pH control. A blending flow was initially set at $25\,liters\,h^{-1}$ and subsequently raised to $50\,liters\,h^{-1}$ to increase the concentrations of Ca^{2+} and Mg^{2+} in the permeate flow to meet irrigation water quality guidelines[11]. Standard instrumentation for offline monitoring of electroconductivity (EC), pH, pressure and flow rate at key points was installed. Composite daily samples of feed water, permeate and concentrate were collected on a regular basis and analyzed for pH, EC and concentration of the ions of principal interest to this study (Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, and HCO_3^-).

An array of solar photovoltaic (PV) modules with a total capacity of $4.2\,kW_p$ was installed in May 2011 adjacent to the desalination plant. It consists of 15 polycrystalline modules (Suntech STP 280 W) organized along three rows for a total surface area of $31.6\,m^2$ (10.0 m ×3.2 m). The modules are inclined at a 45° angle toward the south to maximize the electricity output in the winter season. The system includes three solar controllers with maximum power point tracking (TriStar MPPT, 60 Amp). Twelve battery units (2 V, 750 Ah) and a sine-wave DC/AC inverter (AJ 500-12) connect the solar and desalination sub-units. Since the solar unit was installed near the end of the 2010/11 growing season, which in the Arava is from September to June, the desalination plant was powered with electricity from the local grid during the agricultural experiments described below. During the summer, autumn and winter of 2011, the pilot desalination plant was operated exclusively on solar energy continuously and without interruption over prolonged periods without differences in performance.

Plant materials and management

A $1056\,m^2$ agricultural plot (22 m ×48 m) was prepared in September–October 2010 for crop cultivation in open-field conditions. Owing to the high salinity of the local soil and in line with the common local practice, $30\,m^3$ of soil were transported from the Arava River and distributed at the site. The soil has the texture of loamy sand with EC

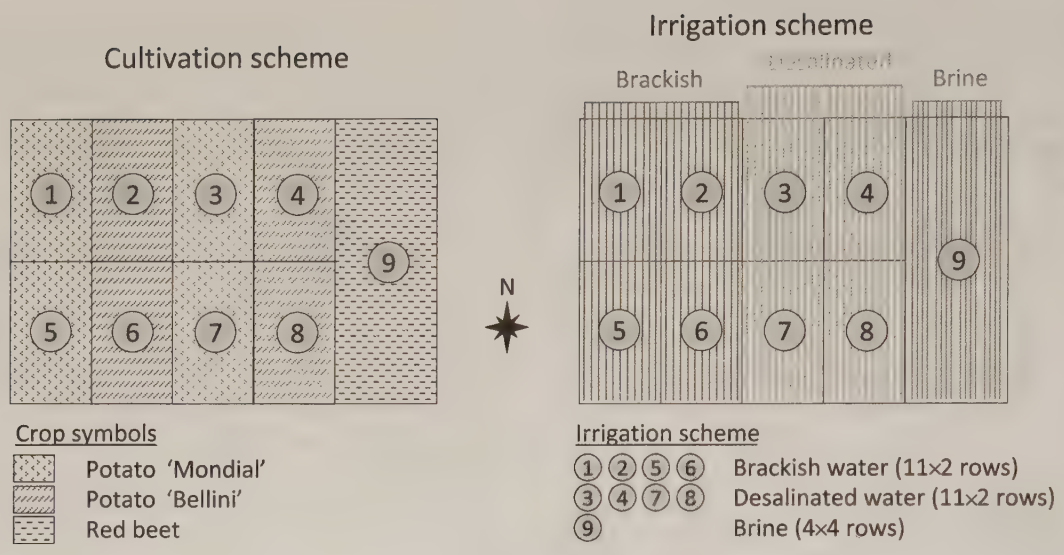

Figure 2. Cultivation and irrigation scheme for potato during the winter cycle.

of $4.7 \pm 0.3\,dS\,m^{-1}$. The contents of N, P and K before the distribution of compost and fertilizer were, respectively, equal to 21.7 ± 1.8, 2.6 ± 0.8 and 80.1 ± 28.2 ppm. The terrain was prepared by distributing compost (50 kg, C = 17%, N = 1.68%, P = 1.36%, K = 2.12%, and C/N ratio = 10) and granular fertilizers mixed into the soil with a rotovator. The irrigation water was supplemented with a liquid nutrient solution (NPK 7–3–7) at a constant concentration of $1\,liter\,m^{-3}$ for all treatments. Pesticides were used according to standard agricultural practices.

Four different staple crops were grown at the experimental site during two growing cycles. During the winter cycle (from November to March), potato (*Solanum tuberosum* L.) cultivars Bellini and Mondial were grown. Diagrams of the subdivisions and irrigation schemes during the winter and spring cycles are given in Figs. 2 and 3, respectively. Seed potatoes were planted on November 1 in 44 parallel rows spaced 90 cm apart. Each row consisted of a 20 cm high, hand dug hummock, and a minimum thickness of 15 cm from the original soil was maintained everywhere. Potatoes were planted in 17 cm deep holes dug on the top of the hummocks. Planting distance in a row was about 30 cm. After sowing, the holes were filled up to 5 cm from the surface, where drip irrigation pipes were installed. The terrain was subdivided into eight equal, 11 m long plots. Half were irrigated with desalinated water, the rest were control plots irrigated with brackish water, with two replicates for each treatment and variety. Sprinkler irrigation distributed 3 cm of the intended final water quality (i.e., brackish, desalinated or concentrate) before sowing and 3 cm after sowing. In both cases, the water was applied in a single irrigation event with 4 h duration. After this initial period, routine irrigation with the drip system was implemented. The irrigation volumes for the control plots were determined based on the guidelines of the

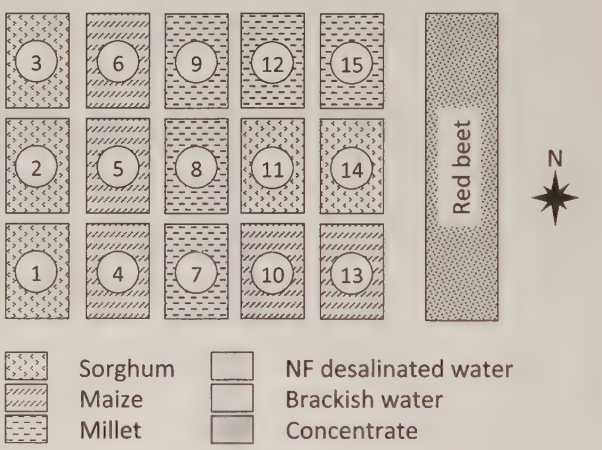

Figure 3. Cultivation and irrigation scheme for maize, sorghum and millet during the spring cycle.

Israeli Ministry of Agriculture (http://www.shaham.moag.gov.il/) and set equal to 80% of the pan evaporation rate, which was measured daily on-site. The pan evaporation rate varied between 3 and $6\,mm\,d^{-1}$ over the winter cycle. The plots irrigated with desalinated water consistently received 25% less water than the control plots. Samples of potato tubers and plants were collected, respectively, on February 18 and 24 from 90 cm wide and 2 m long strips that had been previously cleared. The final harvest was on March 23. The tubers were divided into six categories based on the average diameter and whether they were cracked or otherwise defected.

During the spring cycle (from March to June), the plots were split between three cereal crops: maize (*Zea mays* L., variety 72-10), sorghum (*S. bicolor* L. Moench, variety STT12) and pearl millet (*Pennisetum glaucum* L.). Sowing was on March 2. The terrain was subdivided into 15 plots,

each with a length of 9.5 m and a width of 6 m. Three parallel lines of crops were grown in each plot, each with a net width of 1.5 m. Experiments with brackish water had two replicates, whereas control plots were replicated three times. The routine irrigation strategy was identical to that of the winter cycle, with the experimental plots receiving 25% less water than control plots through drip irrigation. On May 22, a sample of five maize plants and ten millet and sorghum plants were collected from each of the agricultural plots and analyzed for plant height and number of leaves per plant. At final harvest, on June 16, the crops were analyzed for wet and dry matter weight, weight and number of cobs, and marketable yield.

During both cycles, a fraction of the terrain was set aside for the cultivation of red beet (*B. vulgaris* L.), which was irrigated with the concentrated stream from the desalination plant. The red beets were initially grown in a nursery for a period of 2 weeks and subsequently manually planted in the field. Plants were placed into 16 parallel lines arranged into four groups of four parallel lines. A distance of 35 cm was kept between each line, and the emitters were spaced at intervals of 20 cm. The plants were put in the ground at a distance of 5 cm from the drip irrigation pipe. The surface cultivated with red beet was 100 m^2 in the winter cycle and 160 m^2 in the spring cycle. All the concentrate solution produced by the pilot desalination plant was used to irrigate the red beet plants. The final harvests were on February 28 and May 11.

Results

Desalination plant

Pilot NF desalination unit performance matched expectations in terms of reliability of operation, permeate production and energy consumption during both growing cycles. The pilot unit was operated for 24 h d^{-1} over the entire growing periods, with the exception of a 3-week period at the end of the spring cycle, during which a pump malfunction prevented pilot plant operation until the pump could be replaced. Following the contingency plan, the crops were irrigated during this period with desalinated water from the nearby brackish water reverse osmosis desalination plant, which produces drinking water with a similar composition for the field school in Hatzeva.

The NF pilot consistently produced an average permeate flow of 271 liters h^{-1} during the period of observation, corresponding to a daily production of 6.5 m^3. This flow is 30% higher than specified by system design, an outcome that was due mainly to a larger-than-expected feed flow rate. The chemical composition of the feed water showed little variation during the period of observation with the exception of Ca^{2+}, which ranged between 215 ppm on January 16 and 151 ppm on March 6. The operating pressure of the NF membranes was stable in the range of 4.2 – 4.4 bar, and it did not show any increase over the period of operation. The specific energy consumption of the pilot plant was 1.37 kWh m^{-3}.

The desalination unit performed according to expectations regarding abatement of monitored ion concentrations (Table 1). Retention of Cl^- ranged between 54% (February 27) and 75% (January 16), with an average permeate Cl^- concentration of 120 ppm. At the initial blending flow of 25 liters h^{-1}, the concentrations of Ca^{2+} and Mg^{2+} in the permeate were, respectively, 23 and 12 ppm, values that are lower than the recommended minimum concentration of these nutrients for agricultural use (32 ppm for Ca^{2+} and 12 ppm for Mg^{2+})[11]. The blending flow was increased on January 19 to 50 liters h^{-1}, raising the average concentrations of Ca^{2+} and Mg^{2+} in permeate to 45 and 23 ppm, respectively. Such values are well within or above the recommended concentrations. The concentration of SO_4^{2-} was above the minimum recommended value of 30 ppm during the whole period.

The EC of the feed water showed little variation over the observed period, averaging 2.32 dS m^{-1} and with no trend toward increase or decrease over time. EC values of permeate and concentrate were relatively constant at 0.71 and 4.73 dS m^{-1}, respectively. Before the increase in blending flow, the average EC of permeate was 0.58 dS m^{-1}; after January 19, the average EC increased to 0.86 dS m^{-1}. Evaluation of the sodium adsorption ratio (SAR) and sodium/calcium ratio, as indicators of the suitability of the water for agriculture, indicates that irrigation with either the brackish feed water (SAR = 3.7; Na/Ca ratio = 1.17) or the blended permeate water (SAR = 2.9; Na/Ca ratio = 1.78) does not entail a significant risk for reduction of the water infiltration rate in the sandy soil of the Arava[12].

The actualized cost of water was estimated at 2.0 US$ m^{-3} for solar-powered operation, a relatively low value compared with the range of costs of experimental solar membrane desalination units[13]. The cost could be reduced further to 1.1 US$ m^{-3} if the pilot unit was powered by grid electricity, assuming an average electricity price of 0.115 US$ kWh^{-1}. These estimates include the investment costs for both the NF desalination unit and the solar modules (including batteries, charge controller and AC/DC inverter). Operation and maintenance costs were estimated with a yearly replacement rate of 20% for membranes and batteries and a cost of 0.03 US$ m^{-3} for anti-scalants. A project lifetime of 20 years, a discount rate of 2%, 24 h d^{-1} operation, and a plant availability of 95% were assumed.

Crop growth and yield

The number of potato tubers and yield in the final harvest of the winter cycle are shown in Table 2. Healthy tubers are categorized into four diameter ranges, while the cracked and rotted potatoes are reported in two separate columns. The figures for total number and weight

Table 2. Number of tubers and yield (in kg) observed at final harvest for two varieties of potatoes grown at different irrigation water qualities and quantities (means ± SE, $n = 2$).

			Diameter (mm)						
Measure	**Variety**	**Treatment**	**<35**	**35–45**	**45–65**	**>65**	**Cracked**	**Rotten**	**Total per m²**
Number	Mondial	Brackish	22±4	27±7	73±8	77±3	21±9	8±3	28.0±0.4
		Desalinated	29±15	36±5	84±6	67±3	27±5	9±6	31.1±3.0
	Bellini	Brackish	16±3	41±1	116±18	57±4	30±5	24±17	34.9±0.3
		Desalinated	14±4	22±2**	77±7	41±1*	31±4	45±10	28.2±2.2*
Yield (kg)	Mondial	Brackish	0.4±0.0	1.4±0.4	11.3±0.4	25.9±1.3	5.3±2.3	1.2±0.1	5.6±0.1
		Desalinated	0.5±0.3	2.0±0.2	12.3±0.8	22.5±1.4	7.0±1.1	1.6±0.9	5.7±0.2
	Bellini	Brackish	0.2±0.0	2.0±0.0	16.7±3.7	17.1±1.2	5.1±0.6	3.3±2.4	5.5±0.2
		Desalinated	0.2±0.0	1.1±0.1**	11.1±1.6	11.8±0.0*	5.9±0.1	7.2±1.7	4.6±0.4

Note: A two-tailed *t*-test with equal sample size and variance was used to identify statistically significant differences between the experimental and control plots for each variety. Statistical significance is indicated with ** and * for 5 and 10% levels, respectively.

per square meter of agricultural plot include the cracked and rotten tubers.

The average yield in the eight plots was 53.5 tons ha^{-1}, a value that is in line with the initial expectations. The yield was higher for the Mondial variety (56.4 tons ha^{-1}) than for Bellini (50.6 tons ha^{-1}). Results for the Bellini variety were affected by a particularly low yield in one of the plots irrigated with desalinated water, which produced 41.8 tons ha^{-1}, i.e., 18% less than the replicate plot. Overall, there are no statistically significant differences in the yields of potatoes irrigated with desalinated and brackish water. The number and yield of potatoes with diameters >65 mm were lower in plots irrigated with desalinated water than in control plots, but the difference was statistically significant only for the number of Bellini potatoes. The total number of Bellini potatoes per unit area was lower in crops irrigated with desalinated water.

An infestation of *Erwinia carotovora* that affected the plots irrigated with desalinated water more severely is a confounding factor in the interpretation of the results of the winter cycle. *Erwinia* is a common potato pathogen that causes tuber soft rot and blackleg and against which no chemical treatment is known to provide full protection in field conditions. Samples of plants were collected on February 24 (Fig. 4) and were investigated at the Southern and Central Arava R&D facilities, for the presence of infected plants. The results of this analysis indicate that the number of infested plants was 1.7 and 2.7 times higher in desalinated plots for Mondial and Bellini, respectively (Fig. 2). This is consistent with the higher number and weight of rotten tubers collected from plots irrigated with desalinated water for both varieties in comparison with control plots (see Table 2). A higher incidence of the infestation in experimental plots is also suggested by the analysis of the sample of tubers collected on February 18. This sample of healthy plants revealed an increase of 25% in the yield of Bellini plots irrigated with desalinated water compared with control plots. Whether there are mechanisms that link desalinated water irrigation with the *Erwinia* infestation is unknown.

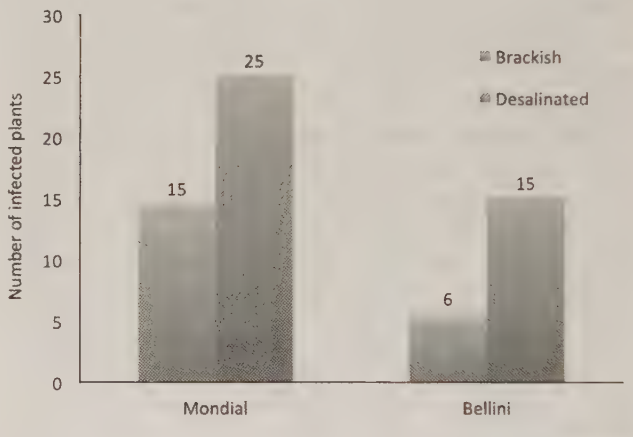

Figure 4. Number of potato plants infected by *E. carotovora* in a sample collected on February 24, 2011.

The results of the analyses at final harvest of the spring cycle for maize, millet and sorghum are shown in Table 3. Both growth measurements and yield are reported.

Irrigation with desalinated water positively affected plant growth in all three crops. Plants in experimental plots were between 23 and 26% taller than in control plots. Similarly, the total dry biomass was 27 and 32% larger in experimental plots for sorghum and maize, respectively. The total wet biomass of maize in experimental plots was larger than in control plots by 45%. We found no significant difference in the number of leaves per plant in maize (data not presented).

A difference in yield was observed only for sorghum (Table 3). Arithmetic mean yield of millet was 34% higher in desalinated than brackish plots, but the difference was not statistically significant probably because of the limited number of replicates. In spite of a larger weight of individual panicles in experimental plots, the yield of maize was not larger than in control plots as determined by a lower number of cobs in experimental plots.

The cultivation of red beet irrigated with concentrate from the desalination unit was successful during both

Table 3. Observed growth measurements and grain yield made at final harvest for maize, millet and sorghum grown at different irrigation water qualities and quantities (means ± SE).

Measure	Treatment	Maize	Crop millet	Sorghum
Plant height (cm)	Brackish	167 ± 3	163 ± 3	179 ± 7
	Desalinated	205 ± 4***	205 ± 4***	221 ± 9***
Plants per plot	Brackish	57 ± 2	–	174 ± 10
	Desalinated	63 ± 2	–	255 ± 37
Total dry biomass (kg)	Brackish	10 ± 1	23 ± 1	32 ± 1
	Desalinated	13 ± 1*	24 ± 1	41 ± 1***
Panicle weight (g)	Brackish	275 ± 8	3.1 ± 0.3	
	Desalinated	333 ± 19**	3.6 ± 0.5	–
Yield ($kg\,m^{-2}$)	Brackish	1.4 ± 0.2	0.09 ± 0.01	0.65 ± 0.02
	Desalinated	1.4 ± 0.0	0.13 ± 0.01	0.71 ± 0.00*

Note: A two-tailed *t*-test with equal variance was used to identify statistically significant differences between experimental and control plots for each crop. Statistical significance is indicated with ***, ** and * for 1, 5 and 10% levels, respectively.

Table 4. Observed yield of red beet irrigated with concentrate during winter and spring cycles (means ± SE, $n = 4$).

	Yield ($tons\,ha^{-1}$)			
Growing cycle	<8 mm	8–11 mm	Cracked	Total
Winter	2.0 ± 0.1	2.5 ± 0.1	0.4 ± 0.1	4.9 ± 0.1
Spring	1.5 ± 0.1*	4.0 ± 0.2**	0.2 ± 0.1	5.6 ± 0.2*

Note: A two-tailed *t*-test with equal sample sizes and variance was used to identify statistically significant differences between the growing cycles. Statistical significance is indicated with ** and * for 1 and 5% levels, respectively.

growing cycles. Plants failed to show any detrimental effect from irrigation water salinity or pests. Table 4 shows the results of the analysis at final harvest for two classes of diameter and for cracked or otherwise defective beets. A higher yield was observed during the spring cycle, when beets were typically larger than during the winter cycle.

Discussion and Conclusions

To date, research on the combination of renewable energy and desalination in agriculture has focused principally on distillation technologies and greenhouse farming. Among the proposed solutions are solar stills, solar greenhouses, enhanced solar greenhouses and hybrid pressure-driven/distillation systems[10,14]. None of these technologies has achieved widespread adoption, at least in part due to high investment costs[15]. The growth of the membrane segment in the desalination market and the plunging prices of PV modules suggest that there may be an unexplored potential for membrane solar desalination. In this study, we investigated the combination of NF membranes and PV power for the desalination of brackish groundwater for application in arid land agriculture at the farm-scale level.

The design of the investigated system reflects the state-of-the-art of membrane solar desalination. The combination of PV modules and pressure-driven membrane desalination is the most thoroughly tested and currently the only commercial technology available for solar-powered membrane desalination in small-scale systems[13]. Particular care is devoted to address some issues that commonly affect the viability of inland desalination in application to the agricultural sector. First, the operation of NF membranes is less energy intensive than reverse osmosis, since the membranes operate at a lower pressure, albeit at a lower salt retention. Modeling of the membrane filtration process with the boundary conditions observed at Hatzeva suggests that NF membranes can operate at a 45% lower pressure than reverse osmosis and with a 40% reduction in energy consumption[10]. That lower energy consumption translates into a lower investment cost for the PV modules, which, thus far, has been the main limiting factor for a wider market penetration of PV-powered membrane desalination[13].

Second, NF membranes allow for a higher permeate concentration of basic nutrients such as Ca^{2+}, Mg^{2+} and SO_4^{2-}, which are essential to plant growth. The operation of the pilot plant during the period described in this paper shows that the implementation of an appropriate blending flow rate between feed water and NF permeate is sufficient to meet the requirements for the application of desalinated water in agriculture. The resulting salinity of the irrigation water is compatible with the tolerance of most salt-sensitive crops ($EC = 0.86\,dS\,m^{-1}$).

Third, the proposed design explores the opportunity for beneficial reuse of desalination concentrate for the cultivation of salt-tolerant crops (i.e., halophytes). The fate of the concentrate is an important issue in inland desalination due to the high cost for its disposal, which has been estimated at about 15% of the total costs[16]. Commonly used methodologies for dealing with concentrate include discharge to surface waters and wastewater treatment plants, deep well injection, land disposal,

Table 5. Water productivity of four staple crops irrigated with brackish or desalinated water.

	Potato				
Productivity ($kg\,m^{-3}$)	**Mondial**	**Bellini**	**Maize**	**Millet**	**Sorghum**
Brackish	6.57	6.46	1.54	0.10	0.72
Desalinated	8.92	7.20	2.06	0.19	1.04
Percent increase (%)	+36	+12	+33	+93	+46

and near-zero liquid discharge[17,18]. Halophyte irrigation has been proposed as a suitable paradigm to convert the management of desalination concentrate from a disposal problem to a water management opportunity[19]. Halophyte irrigation with desalination brine presents soil and water management constraints that are analogous to those of brackish water irrigation. Only a limited number of halophytes have been investigated in the literature, including forage, biofuel and oilseed crops, such as *Salicornia* spp.[20,21]. The present research contributes to this growing literature by testing the use of desalination concentrate to irrigate red beet, a moderately salt-tolerant crop with good nutritional properties and commercial value. Red beet was successfully managed to consume the effluent of the pilot plant over two growing seasons, suggesting that this can be a suitable option for moderately saline concentrate from brackish water desalination.

The principle objective of this study was to provide a proof of concept of the technical feasibility of solar membrane desalination in the context of arid, inland agriculture at the farm level. The four investigated staple crops were accordingly selected based on their widespread adoption and range of salt tolerance (from moderately tolerant to moderately sensitive) rather than their expected economic return on initial investment. We hypothesized that irrigation with desalinated water would result in an appreciable improvement in resource use efficiency both for water and fertilizers per unit of marketable yield compared with the current practices involving brackish water irrigation. Table 5 summarizes the water productivity for the four investigated crops. It is calculated as the ratio between the marketable yield (in kg) and the total volume of water used for irrigation (in m^3). The percent increase in productivity for desalinated water irrigation is also presented in the table. Since the liquid fertilizer was added to the irrigation water at constant concentrations for all treatments, the results for fertilizer productivity are analogous to those for water.

Table 5 shows that once the actual irrigation volumes are taken into account, the water productivity of crops irrigated with desalinated water was consistently higher, including for the Bellini potato variety, i.e., the only crop for which a (non-statistically significant) yield decrease was observed when irrigated with desalinated water. The highest increase in water productivity (+93%) was found for millet.

The two important factors in the observed change in water productivity are the salinity and the application rate of the irrigation water. In similar climatic conditions, a previous study observed a progressive yield decrease in maize for continuous irrigation with brackish water at different EC levels[22]. If applied to the salinities measured in this study, their best-fit regression would predict a 13% reduction in the yield for brackish water irrigation compared with the optimal freshwater salinity ($EC = 0.84\,dS\,m^{-1}$). A considerable variation in salt tolerance exists among cultivars[23]. Experiments with potatoes in southern Israel led to the conclusion that the yield under brackish water irrigation is substantially affected by external stress factors such as heat waves, time of application of the brackish water and soil salinity[24,25]. Under favorable conditions, no significant effect on the yield of the potato variety Desiree was observed up to $2.42\,dS\,m^{-1}$.[24] Under stress conditions due to heat waves, however, the yield closely approaches the response curve proposed by Maas and Hoffman[26] with a 12% linear decrease in yield for each additional $dS\,m^{-1}$ above a threshold of $1.7\,dS\,m^{-1}$. In the conditions under study in the present investigation, such a relationship would predict a yield increase of 7% for irrigation with desalinated water. Similar estimates of yield variability have been measured with equal application rates of irrigation water and cannot be directly compared with the results of this study. Research on the effect of the amount of applied irrigation water on transpiration, yields and leaching fractions of bell pepper, showed that yield response is highly dependent on both the water salinity and its application rate, the impact of salinity being highly reduced in the presence of high rates of leaching[8].

In conclusion, the results of this study support the hypothesis that solar-powered membrane desalination is a technically viable and more resource efficient alternative to brackish water irrigation, at least in the context of arid agriculture at Hatzeva in the Arava Valley of Israel. Further research should investigate whether higher water savings can be achieved without adversely affecting water productivity and marketable yield. Moreover, the costs and benefits of the system should be evaluated in a wider range of contexts. In particular, the benefits of desalination are expected to be highest for elevated brackish water salinities—since the energy consumption, and thus the costs for desalination, do not increase linearly with

the salinity of the feed water—and in combination with the cultivation of salt-sensitive cash crops that cannot be grown with brackish water (e.g., strawberries and asparagus). The performance of the proposed scheme should be tested under nutrient limitation such as that induced by low soil fertility, a condition that is observed, for instance, in many regions in Africa, and in longer-term studies, to ensure that soil integrity is maintained when irrigated over prolonged periods. Although the system operated with relatively little maintenance during the reported period, operational tests with solar power for longer durations are required to evaluate the risks associated with pump malfunctions or battery replacement requirements as they apply to remote areas. Overall, we suggest that solar desalination has the potential to become an additional resource within a portfolio of strategies to improve the sustainability of agriculture and adapt to climate change in arid and remote areas that are freshwater-poor but have extensive brackish water resources, as is the case for many areas in the MENA region.

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Rurality and agroecosystem sustainability: a case study at farm-field level in Terceira Island (Portugal) and in Viterbo Province (Italy)

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Abstract

Defining the balance between socio-economical and bio-physical aspects in order to promote sustainable development in agriculture is a fundamental challenge for researchers. The aim of this study is to assist in constructing a science of sustainability in agriculture and to assess sustainability in various types of agroecosystem managements characterized by different agricultural and rural developments. This study evaluates sustainability on Terceira Island (Portugal) and in the Province of Viterbo (Italy) by using selected agroecosystem sustainability indicators capable of achieving an energetic and monetary input/output analysis. Overall, results showed two rural and agricultural realities that outline two different responses to world market demand, which are partly due to specific rural histories. In terms of energy supply, Terceira and Viterbo dairy farms use the same amount of input but in monetary terms the level of input is more than double in Viterbo (€1651 ha^{-1} versus €616 ha^{-1}) which is due to the lower cost of direct energy (e.g., fuel) on the island. The use of direct energy input (fuel, electricity and lubricants) on the farms in Viterbo decreases in mixed farm systems and is at its minimum on dairy farms. On the other hand, the use of indirect energy input (fertilizers, herbicides, pesticides, seeds and feedstuffs) is greater on Terceira farms compared with those in Viterbo (0.76 versus 0.60, respectively). Generally speaking, the crops grown on Terceira are not diversified and this has caused environmental issues on the island due to the milk production that is mainly exported. In Europe, more intellectual and financial resources for measuring and monitoring sustainability conditions in agriculture are necessary, in order to appropriately inform decision makers at both institutional and individual level.

Key words: indicators, input/output, energy/money, dairy farm, renewable energy, food production

Introduction

Sustainable development includes the need for humans to grow food by means of agriculture as well as to maintain natural environments for ecological services other than food[1–5]. The search for a convergence between production and protection is therefore a major challenge to future society at both local and global level. In order to achieve sustainable human activity systems such as agriculture, scientists should supply the necessary data for establishing a responsible culture for sustainability. In Europe, which has old agricultural traditions, examples of rural development should be better acknowledged, explored and, if sustainable, disseminated as meaningful case studies of traditional knowledge and wise land use[6]. Traditional types of agriculture, more tailored to both environmental constraints and local population requirements, are likely to meet sustainability principles more than modern (conventional) agriculture, where the uniformity and homogeneity of large fields of monocrops and the exclusion of livestock are often incompatible with environmental quality and the conservation of biological resources[7]. Among the activities for improving planning and management systems, data and information

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Figure 1. Geographical representation of the compared areas (Terceira Island and Viterbo Province).

collection is crucial; therefore, it is recommended[8] that 'countries could develop systems for monitoring and evaluating progress towards achieving sustainable development by adopting indicators that measure changes across economic, social, and environmental dimensions'. In agroecology, the tools suitable for this task[9–17] are generally called Agriculture Sustainability Indicators (ASIs) and their development and use have been largely promoted in research as a necessary instrument for understanding agroecosystems performance, facilitating judgments and suggesting solutions for improving sustainability in agriculture. Generally, ASIs are developed on the base of the general input/output model of agroecosystem analysis according to the paradigm system[12,18].

From the system point of view, sustainability is regarded an emergent characteristic of ecosystems[19], which is the result of integration among the ecosystem components where ecological integrity is recognized as a driving force in promoting sustainability and its outcome gives us the possibility of maintaining a balanced and adaptive community (biological integrity) to continue self-organized development in a sustainable way[20]. There is a double purpose for developing ASIs, both epistemological and practical, representing, respectively: (a) an efficient instrument of enquiry for studying agroecosystem functioning and performance according to an input/output approach; and (b) a relevant knowledge base for both the designing of sustainable agroecosystems and decision-making processes.

This study concerned an assessment of agricultural sustainability on Terceira Island (Azores, Portugal) and in the Province of Viterbo (Central Italy), based on the use of ASIs and a comparison approach, in order to achieve the following results: to produce knowledge for constructing a science of sustainability in agriculture based on the use of transdisciplinary tools, such as indicators of agricultural sustainability at farming system levels; the production of knowledge useful for expressing judgments on the sustainability of different cropping and animal system management, facilitating the identification of some best agricultural practices; for identifying various agroecological problems of the agroecosystems in question, and to find the causes of these problems in the farms' management approach (spontaneous or induced). The two areas were chosen in order to pursue these objectives analyzing the agricultural and rural result of different historical paths, one of which (Terceira) relatively short and isolated and the other (Viterbo) millennial and layered.

Material and Methods

The Azores archipelago and Terceira Island

The Azores archipelago, located in the high subtropical zone (northern hemisphere; Fig. 1), was discovered in 1439, there were no inhabitants, and the islands were gradually populated by settlers. Today (Table 1), the

Table 1. Viterbo Province and Terceira Island features.

	Viterbo Province	Terceira Island
Latitude–longitude	42°25′N–12°06′E	38°40′N–27°10′W
Total area (km^2)	3612	400
Agriculture (% of total)[1]	57.9	20.0
Total population (thousand)	289	55
Density (people km^{-2})	79.5	138.5
In agriculture (% of total)	14.4	28.0
Temperature (max.-min.-average)	23.8–6.0–13.8[2]	29.6–3.4–14.6[2]
Rainfall (mm/yr—day/yr)	766–76	1500–200
Insulation (h/yr)	2500	1200
Soil type	Sandy loam/clay loam	Sandy loam/clay loam
pH	5.5–6.7	5.5–6.7
Organic matter (%)	1–2	5–20
Water retention	Low	High
P retention	High	High
Total cattle population	75,000	240,000
Milk cows (% of total)	38.7	41.6
Biomass (t ha^{-1} yr of dry matter)[3]	5.0 (*Lolium rigidum* L.)	10.0 (*Lolium perenne* L.)
Farm land use		
Herbaceous crops	52	27
Tree crops	15	5
Grassland and pasture	7	53
Woodland	20	9
Others use	6	6

[1] Reported to utilized agricultural area.
[2] Respectively, from weather observations in low land—hilly areas (0–600 m a.s.l.) and in hilly pasture areas (400 m a.s.l.).
[3] Average for lower and higher lands.

Azores are an autonomous region (three groups consisting of the nine main islands; São Miguel, Terceira, Pico, São Jorge, Santa Maria, Faial, Flores, Graciosa, and Corvo) of the Portuguese Republic. The Azores are a predominantly rural territory (with a demographic density less than 150 inhabitants km^{-2}).

In terms of climate (Table 1), the Azores are located in a large subtropical semi-permanent center of high atmospheric pressure called the 'Azores High' (also known as North Atlantic High-Anticyclone or Bermuda High-Anticyclone), which is the dominant factor for the average archipelago meteorological conditions (which may lead to summer water deficit in agriculture). Local climate (Table 1; Fig. 2a) can be classified as wet temperate; and as temperature changes with altitude, the climate can be cold and wet in the mountains where it rains intensively. The air moisture content (annual average around 80%) increases from east to west in the archipelago, from south to north on each island and generally with altitude. Therefore, a climatic phenomenon called the 'North Atlantic Oscillation' (due to seasonal atmospheric pressure fluctuations at sea-level, between the Icelandic Low and the Azores High) is responsible for much of the variability of weather conditions; during this season the agricultural activity is affected by storms and winds transporting salt, which damages the vegetation. Owing to the volcanic origin of the Azores, the soil is andisols (highly permeable, with a high content of organic matter, rich in potassium and nitrogen; Table 1).

The edapho-climatic conditions of the islands offer excellent conditions for cattle production and determine that the rural landscape is dominated by pastures. In economic and technical terms, the agriculture in the Azores is principally supported by dairy production, in extensive or semi-extensive regime, where meat is becoming an important product. Grasslands for dairy production are generally located at different altitudes: below 400 m ('lower grasslands') and between 400 and 600 m high ('upper grasslands'). The productivity of the lower grasslands decreases in summertime, between June/July and October. During that period the herds move to the fresh upper lands, where there is more moisture in the soil. During the coldest period of the year, between October and March/April, the grass grows thicker in the lower lands due to the higher temperatures, and so the herds are transferred to the lower lands (Fig. 2b).

The cultivation of cereals (especially wheat) was the first agricultural attempt to establish a local economic activity. The best agricultural methods such as rotation and legume cultivation were not used and this caused a decrease in soil fertility. Cereals were therefore substituted by different crops, creating monoculture cycles. During the second half of the 19th century, some agricultural

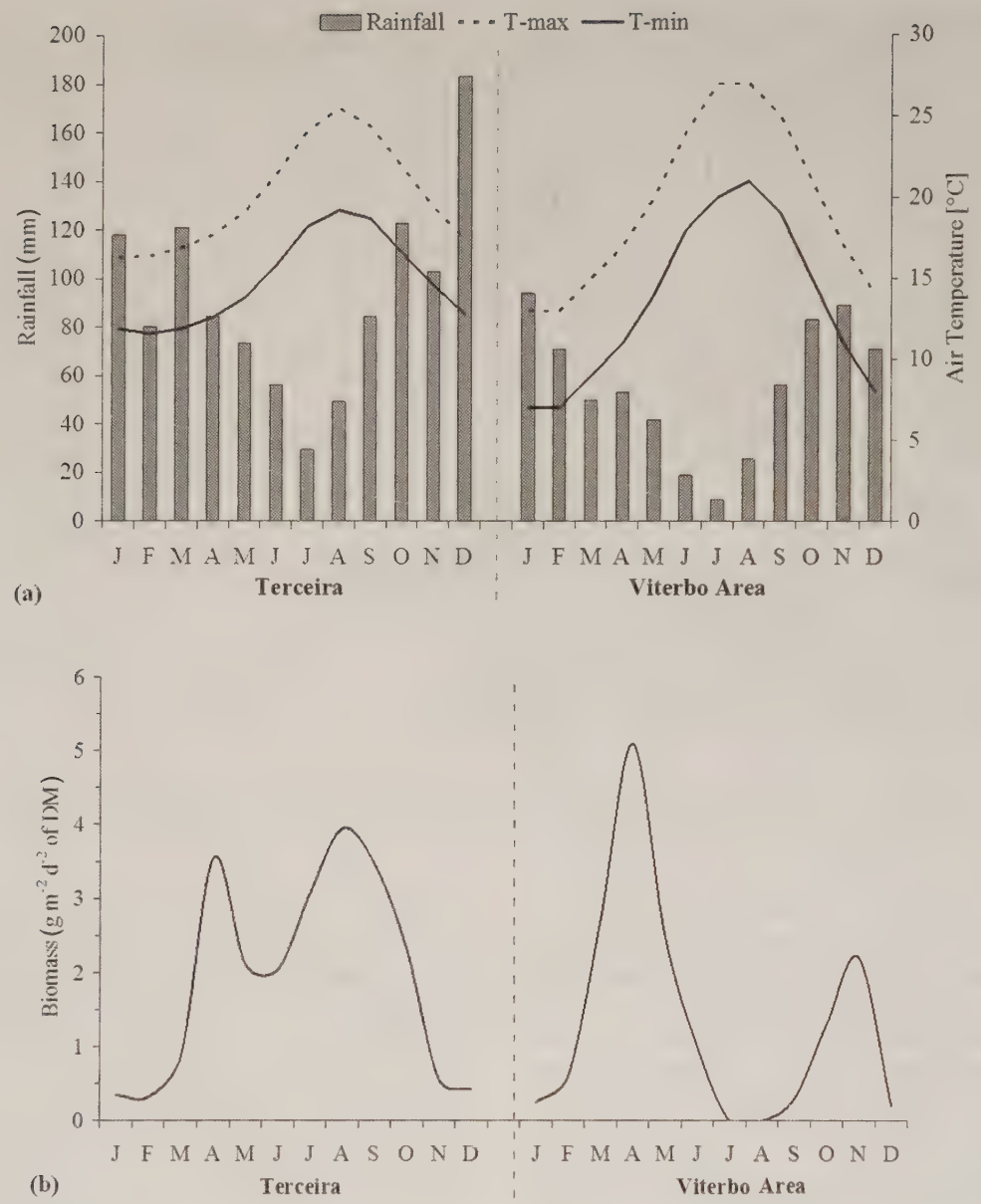

Figure 2. General tendency of rainfall and average temperature (a), and biomass accumulation in monitored grassed swards (b) in Terceira and Viterbo area.

practices improved cattle breeding and, interspersed with some periods of crisis, some decades later the industrialization of dairy products transformed the sector into the most important economic activity in the archipelago. Today, the relative importance of agriculture in the regional economy is significantly higher when compared with European and national averages.

Despite the intrinsic heterogeneity of the Azores, for this study we chose the Island of Terceira as it represents the status of agriculture in the Azores better than the other islands (i.e., São Miguel). In the Azores, Terceira Island represents 20% of the utilized agricultural area, 23% of the agricultural holdings of the Azores, 23% of the agricultural population and 25% of the bovine population[21]. In general terms, the Azorean economy is a typical example of a small insular and peripheral region.

The Province of Viterbo in Central Italy

The Province of Viterbo (also called Tuscia) is located in Central Italy (Fig. 1) in the Northern part of the Region of Latium in a territory (about 70% hilly) that can be divided roughly into four geographical regions: coastal-plain area; hilly area, mountain area and inland plain area (Tiber valley). Only 15% of the resident population lives in rural areas and agricultural workforce represents 7% of the total inhabitants of the Province (2% is the national average). Central Italy has a typical Mediterranean climate with different microclimates, principally due to altitude and distance from the sea. Rainfall occurs principally during the winter season (Fig. 2a) and in spring and autumn the availability of water is guaranteed from winter stocks and moderate and frequent rainfall, respectively; in

summer, the high temperatures and limited rainfall affect the crop yields. Mainly for these reasons, the crop biomass production occurs principally during springtime (Fig. 2b) forcing farms with cows (or other herbivores) to provide for the dry season with fodders and silages. The soil in this area is volcanic and it is classified as sandy loam and sandy clay loam, with low water retention, 5.5–6.7 of pH, 1–2% of organic matter and high phosphate retention (Table 1). This territory has a long agricultural history and traditions. The rural development of this area is linked to rural Greek and Roman metaphysical reflections on human–land relationships, as expressed in the concept of 'agricultural thinking' which also includes non-agricultural activities[22]. During Roman times, the original family-farm structure was partially replaced with a land cultivation model based on large market-oriented plots owned by aristocrats with a predominantly servile labor force frequently called *latifundia*[23]. In most of Central Italy, the family-farm structure continued to operate in medieval times and created a synergic effect between the people and the fields. Later in the Renaissance, several new types of crops coming from the 'New World' were grown and large amounts of swamp land were reclaimed and cultivated. This type of family farm agriculture can be well defined as 'promiscuous' due to intimate sustainable conjunction of its components (e.g., the human activities, the natural resources and the territory). In the second half of the 20th century, conventional agriculture based on farm specialization, heavy external inputs and a different vision of rurality undermined the basic structure and functioning of traditional family-farm agroecosystems, replacing the flow of solar energy with the flow of auxiliary energy derived from fossil fuels[24,25]. Today's conventional farming tends toward monoculture, homogenizing the production, the inclusion of necessary chemical fertilizers and chemical pesticides, with a long-term goal of establishing a nearly ideal industrial growing environment for crops and animals[7]. In such a scheme, major structural changes, such as the tendency to separate crops from animal husbandry and the renunciation of the cultivation of perennial fodder crops in rotation, are inevitably linked together. Today, there are 38,000 farms in the Province of Viterbo (2.5% with cattle and 0.7% dairy farms—in 2000 there were about 39% fewer farms than 1990) distributed on 280,000 hectares of agricultural land (the average farm area is 7.4 ha). Farmers are about 7% of the total population. The land area used for agricultural activities in the province is between 60 and 70% of the total land area. The percentages of the land use are as follows: 52% herbaceous crops (37% durum wheat, 21% annual forage —mainly clover, 14% perennial forage—mainly alfalfa, 7% industrial crops, 3% corn, and 18% other herbaceous crops), 15% tree crops (42% hazelnut, 34% olive, 12% vineyard, 7% chestnut and 5% other tree crops), 7% grassland and pasture, 20% woodland, 3% non-utilized land and 3% of other use. In the Province, there are more than 29,000 cattle (in 2000 there were about 12.9% fewer cattle than in 1990) and an average of 34 milking cows per farm[26].

Farm sustainability issues

In agroecology, agroecosystem sustainability indicators (developed on the base of input/output models elaborated from the system paradigm) have become a useful tool in research as an instrument for studying agroecosystems; furthermore, in line with recent protocols, indicators of farm structural diversity can be equated to farm sustainability[27,28]. Therefore, the proposed indicators (i) are calculated on incoming and outgoing farm materials, and (ii) some aspects of the farm layout are also taken into account. Despite their apparent simplicity, these indicators are readily interpretable by farmers and bridge communication between scientists and society.

The input/output model of agroecosystem analysis has already been adopted in previous studies concerning ASIs[12,14,29–33]. By analyzing a farm system as a process that transforms inputs into outputs in terms of energy, money, material and/or information, it is possible to calculate indicators of transformation efficiency and thus assess and judge the functioning of the agroecosystem. This methodology allows for rationalizing the on-farm choices and decisions, since it is possible to focus on three modifiable factors: the type-amount of input, the type-amount of output and the organization of the agroecosystem components. In this context, it is important to note that today the on-farm choices, and the decision-making processes that affect them, are not significantly influenced by the results of the indicators[34].

In this study, a hierarchical model of agroecosystem input/output analysis was used where a farm is regarded as a whole with interacting subsystems (Fig. 3), such as different cropping systems and the animal husbandry system, each monitored according to the input used and the output produced.

For an assessment and comparison of agroecosystem performance in different farming systems, it is essential to establish how they are: (i) composed (i.e., land use, crop and livestock diversity) and organized (i.e., prevalent use of solar energy or auxiliary energy), and (ii) how they transform resources. In order to describe these two characteristics, in this study the indicators were divided into two groups: ASIs and agroecosystem functional indicators (AFIs) (Table 2), due to the need for understanding the complex nature of agroecosystems. ASIs describe the composition and organization of the system's components (i.e., the resources that were used in the production process such as land, crops, animals and materials) and AFIs describe the efficiency with which those resources were used (i.e., output/input or input/output ratios). Both kinds of indicators were calculated in terms of money and energy values on all incoming and

Table 2. ASIs and AFIs.

Name and abbreviation	Formula	Meaning
ASIs		
Compositional		
Farm area (FA)		Expressed in hectares, is an important indicator that shows the amount of territory subject to the farmer's choices
Utilized agricultural area (UAA)	= PL/FA	Expressed in term of FA percentage, describe the amount of territory used for agricultural activities respect to the managed territory
Fodder area (FO)	= A/PL	Expressed in term of UAA percentage, describes the amount of agricultural area directly used for livestock nutrition and management (i.e., annual and pluriannual forage land, and pasture land)
Cows density (CD)	= CW/FFA	Expressed in terms of number of milking cows per hectare of fodder area, describes the land use intensity referred to livestock rearing
Organizational		
Energy intensity (EI)	= TEI/PL	Expressed in terms of total input per hectare of productive land, describes the quantity of external direct (fuel, electricity and lubricants) and indirect (fertilizers, herbicides, pesticides, seeds and feedstuffs) energy annually used on the farm
Direct energy dependence (DED)	= DE/TEI	Expressed in terms of percentage of direct external input with respect to the total energy intensity
Indirect energy dependence (IED)	= IE/TEI	Expressed in terms of percentage of indirect external input with respect to the total energy intensity
AFIs		
Milk production (MP)	= M/FFA	Expressed in terms of thousands liters per hectare of fodder crops, describes the relationship between milk production and land use
Protein production (PP)	= pp/Mp	Expressed in terms of protein weight percentage, describes the milk quality, which is important especially in cheese production
Input efficiency (IEff)	= i/O	Expressed in terms of intensity, i.e., amount of each production factor per unit of output

PL, hectares of productive land directly used for agricultural activities as herbaceous crops, tree crops and pastures (roads, stables, wells, and other human infrastructures are excluded); A, hectares of productive land used to gratify animals in terms of food and movement (roads, stables, and other human infrastructures are excluded); CW, number of milking cows; FFA, hectares of fodder area in the farm; TEI total energy input; DE, total amount of direct energy placed in the farm during 1 year; IE, total amount of indirect energy placed in the farm during 1 year; M, 1000 liters of milk products in the farm during 1 year; pp, 1000 kg of protein products in the farm during 1 year; Mp, 1000 kg of milk products in the farm during 1 year; I, amount of input from one production factor; O, amount of output from the final product (i.e., milk, crop yield).

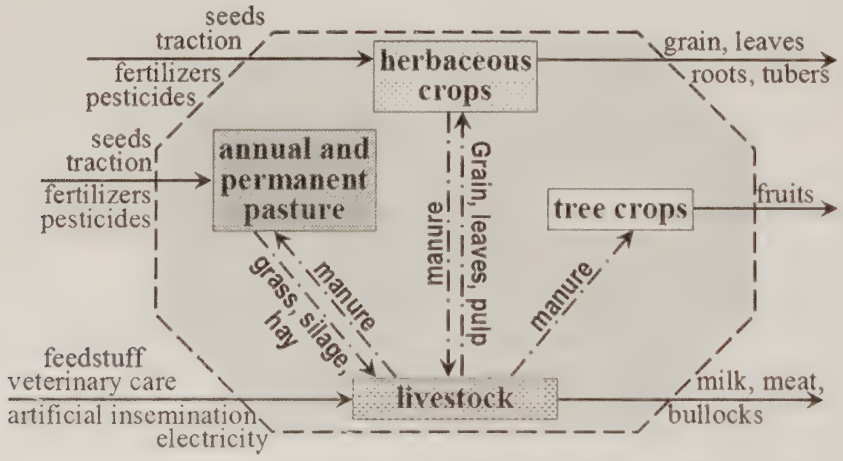

Figure 3. Hierarchical model of agroecosystem input/output analysis.

outgoing materials managed by the farmers and therefore dependent on their decisions. With this approach, and using energetic and monetary accounting criteria, the farm was analyzed in economic (socio-cultural values) and thermodynamic (bio-physical entities) terms. The AFIs were used to highlight the most suitable organization for making better use of the system's natural resources (e.g., solar radiation, soil organic matter and

Table 3. Conversion factors: principal energetic and monetary values applied.

	Energy (J)	Money (€)	
		Viterbo[1]	Terceira
Direct energy input			
Fuel (diesel)	45.6 MJ kg^{-1}	0.87 € kg^{-1}	0.37 € kg^{-1}
Lubricants	4.0 MJ kg^{-1}	2.70 € kg^{-1}	3.22 € kg^{-1}
Electricity	3.6 MJ kWh^{-1}	0.10 € kWh^{-1}	0.001 € kWh^{-1}
Indirect energy input			
Feedstuff	13 MJ kg^{-1}	0.74 € kg^{-1}	0.19 € kg^{-1}
Seeds	10 MJ kg^{-1}	1.27 € kg^{-1}	1.39 € kg^{-1}
Herbicides[2]	135 MJ kg^{-1}	127.00 € kg^{-1}	40.0 € kg^{-1}
Fungicides and insecticides[1]	220 MJ kg^{-1}	25.00 € kg^{-1}	9.0 € kg^{-1}
Fertilizers[2]			
Nitrogen (N)	65 MJ kg^{-1}	0.67 € kg^{-1}	1.3 € kg^{-1}
Phosphorus (P_2O_5)	15 MJ kg^{-1}	0.79 € kg^{-1}	0.82 € kg^{-1}
Potassium (K_2O)	10 MJ kg^{-1}	0.60 € kg^{-1}	0.35 € kg^{-1}
Output			
Milk	3.11 MJ kg^{-1}	0.37 € kg^{-1}	0.24 € kg^{-1}
Cow meat	13.81 MJ kg^{-1}	2.66 € kg^{-1}	–
Pork meat	17.16 MJ kg^{-1}	1.30 € kg^{-1}	–
Chestnuts	14.61 MJ kg^{-1}	1.18 € kg^{-1}	–
Tree crops fruits	2.14 MJ kg^{-1}	0.99 € kg^{-1}	–
Hazelnuts	26.67 MJ kg^{-1}	0.56 € kg^{-1}	–
Olives	14.88 MJ kg^{-1}	0.98 € kg^{-1}	–
Grapes	1.91 MJ kg^{-1}	0.35 € kg^{-1}	–
Cereal grains	14.70 MJ kg^{-1}	0.15 € kg^{-1}	–

[1] Prices are referred to conventional farm products but some Italian farms analyzed are organic and for these organic prices were considered.
[2] Values are referred to units of active principle in solution or fertilizer units and different active principles or commercial products are used in the two ecoregions.

atmospheric nitrogen) rather than the imported, non-renewable resources.

In 2003, two groups of typical farms of Central Italy[33] and Terceira Island[35] were selected. A group of 31 farms was identified in the Province of Viterbo, 16 of which were mixed farms (farms with crops and livestock; four of which were dairy farms) and 15 were non-mixed farms (farms without livestock). Following the same pattern (0.08% of the regional number of farms), a group of ten mixed farms was identified on Terceira Island (exclusively dairy farms, as the main support of local agriculture).

The database for the study was obtained by integrating data from farming associations, account books and other documents (e.g., application forms for European funds) with data from direct interviews with the farmers (both referring to 5 years of information, 1998–2002). Only the variable costs were considered among economic inputs and human labor was not included. In order to obtain both an energy and a monetary analysis, each input and output (defined in terms of quantity) was translated into energetic values (converting the biomass of inputs and outputs into energetic terms, by means of conversion factors derived from the reported scientific literature) and monetary values (referring to market prices in 2000 in Province of Viterbo and Terceira Island, respectively). Only milk was considered as an output in the analysis of milk production since meat and other subproducts were not considered. The principal energetic and monetary conversion factors used are reported in Table 3.

Results

The results (Table 4) show that the presence of livestock plays an important role in defining the farm size in the Province of Viterbo and that an average dairy farm on Terceira Island is a quarter of the size compared with those in the Province of Viterbo (19.2 ha versus 77.7 ha, respectively). The UAA indicator shows that about one-tenth to one-fifth of the selected farm area in the Province of Viterbo is non-cultivated land (mainly represented by small woods and hedges), whereas on Terceira Island these values are much higher (mainly represented by large field borders—hedges and dry stone walls—and woods at higher altitudes). In the Province of Viterbo, the largest percentage of land cultivated with fodder crops was observed on dairy farms (73.3%) but non-mixed farms (without animals) also include fodder

Table 4. Description of the selected farm agroecosystems through some ASIs and AFIs (standard error values are reported in brackets).

	Viterbo			Terceira
	Non-mixed	**Mixed farms**	**Dairy farms**	**Dairy farms**
FA (ha)	39.0 (±17.6)	88.7 (±16.1)	77.7 (±12.5)	19.2 (±5.9)
UAA (%)	88.0 (±3.9)	89.8 (±2.8)	83.8 (±3.3)	45.9 (± 7.0)
FO (%)	25.9 (±7.3)	63.3 (±5.3)	73.3 (±6.9)	92.0 (±6.9)
CD (cows ha^{-1})	–	–	1.2 (±0.2)	1.2 (±0.7)
MP (10^3 l ha^{-1})	–	–	7.3 (±2.2)	4.1 (±1.6)
PP (%)	–	–	3.28 (±0.5)	3.20 (±0.6)

Table 5. ASIs of energetic and monetary intensity (standard error values are reported in brackets).

	Viterbo			Terceira
ASIs	**Non-mixed**	**Mixed farms**	**Dairy farms**	**Dairy farms**
EI – (GJ ha^{-1})	16.07 (±3.69)	27.06 (±6.09)	39.44 (±11.73)	45.62 (±8.78)
Electricity	0.45 (±0.25)	1.88 (±0.84)	3.86 (±1.68)	0.35 (±0.62)
Fuel	8.83 (±2.79)	7.83 (±1.19)	10.13 (±2.44)	10.66 (±5.75)
Lubricants	0.010 (±0.003)	0.010 (±0.002)	0.013 (±0.005)	0.07 (±0.07)
Fertilizers[1]	3.77 (±0.94)	3.40 (±1.58)	0.20 (±0.10)	11.38 (± 6.99)
Herb. & pest.[1]	1.29 (±0.54)	0.39 (±0.28)	0.01 (±0.01)	0.44 (±0.39)
Seeds	1.72 (±0.92)	0.62 (±0.13)	0.64 (±0.32)	0.23 (±0.15)
Feedstuffs	–	12.93 (±5.64)	24.59 (±9.65)	22.50 (±12.89)
EI – (€ ha^{-1})	597 (±144)	1046 (±320)	1651 (±582)	616.5 (±116.6)
Electricity	11 (±6)	46 (±20)	93 (±41)	8.6 (±13.6)
Fuel	131 (±41)	116 (±18)	150 (±36)	87 (±45.9)
Lubricants	5 (±1)	5 (±1)	7 (±3)	5.5 (±0.4.9)
Fertilizers[1]	79 (±15)	57 (±23)	2 (±1)	133.9 (±69.9)
Herb. & pest.[1]	171 (±57)	60 (±33)	12 (±5)	20 (±10.3)
Seeds	200 (±106)	72 (±15)	74 (±37)	31.5 (±22.7)
Feedstuffs	–	690 (±301)	1313 (±516)	329.9 (±193.9)

[1] Annual average of the whole crop rotation.

crops in the crop rotations (25.9%), mainly legumes for N-fixation. On the other hand, on Terceira Island, fodder crops cover a much larger area of farm land than other crops. Concerning the surface of farm land cultivated with fodder, similar values were observed regarding cow density on Terceira Island and in the Province of Viterbo, while milk production was higher in Viterbo even if in both areas the Frisona race was the most numerous breed.

In terms of energy intensity (GJ; Table 5), the results of ASIs show that in Viterbo the energy input increases in the presence of livestock (EI is more than double on dairy farms compared with non-mixed farms; 39.44 and 16.07, respectively). On Viterbo dairy farms, feedstuff and fuel represent the most relevant input (62 and 26%, respectively). On Terceira, feedstuff and fertilizers are the main components of energy input (49 and 25%, respectively). In monetary terms (€; Table 5), in Viterbo EI increases in the presence of livestock and is almost triple on dairy farms compared with non-mixed farms (€1651 and €597, respectively). On dairy farms in Viterbo, EI is about 2.7 greater than on Terceira Island and the value of feedstuff is greater than fuel (80 and 9%, respectively). On Terceira Island feedstuff is the highest energy value (53%), followed by fertilizers (22%) and fuel (14%).

By considering energy inputs as direct and indirect (Table 6), the results show that on the farms in Viterbo the use of direct energy inputs decreases in mixed farm systems and is at its minimum on dairy farms. On Terceira farms, the use of direct energy inputs is practically half compared with those observed in Viterbo. On the other hand, the use of indirect energy inputs (fertilizers, pesticides, etc.) is significantly greater on Terceira farms compared with those in Viterbo (0.76 versus 0.60, respectively). In monetary terms, there is little difference concerning the use of direct and/or indirect energy inputs between Viterbo and Terceira farms: the monetary distribution of direct (0.19 versus 0.17) and indirect (0.81 versus 0.83) energy inputs on dairy farms have similar values.

Table 6. ASIs: direct (DED) and indirect (IED) energy dependence indicators (standard error values are reported in brackets).

ASIs[1] Symbols	Viterbo			Terceira
	Non-mixed	Mixed farms	Dairy farms	Dairy farms
DED – (J/J)	0.55 (±0.07)	0.46 (±0.06)	0.40 (±0.04)	0.24 (±0.06)
DED – (€/€)	0.32 (±0.06)	0.25 (±0.04)	0.19 (±0.03)	0.17 (±0.05)
IED – (J/J)	0.45 (±0.07)	0.54 (±0.06)	0.60 (±0.04)	0.76 (±0.06)
IED – (€/€)	0.68 (±0.06)	0.75 (±0.04)	0.81 (±0.03)	0.83 (±0.05)

[1] Annual average of the whole crop rotation.

Table 7. AFIs: production factors input efficiency (IEff) in energetic and monetary terms (standard error values are reported in brackets).

	Viterbo			Terceira
	Non-mixed	Mixed farms	Dairy farms	Dairy farms
AFIs – (J/J)				
Electricity	0.0493 (±0.0132)	0.0778 (±0.0214)	0.2417 (±0.0734)	0.0093 (±0.0135)
Fuel	0.9244 (±0.5451)	0.4387 (±0.0661)	0.5767 (±0.0888)	0.4010 (±0.1813)
Lubricants	0.0015 (±0.0010)	0.0005 (±0.0001)	0.0006 (±0.0001)	0.0026 (±0.0022)
Fertilizers[1]	0.1733 (±0.0595)	0.1691 (±0.0907)	0.0138 (±0.0011)	0.4106 (±0.1806)
Herb.- pest.[1]	0.1281 (±0.0700)	0.0171 (±0.0082)	0.0002 (±0.0001)	0.0150 (±0.0067)
Seeds	0.1401 (±0.0585)	0.0413 (±0.0081)	0.0304 (±0.0072)	0.0087 (±0.0051)
Feedstuffs	–	0.4754 (±0.1001)	1.0847 (±0.0675)	0.7717 (±0.2397)
AFIs – (€/€)				
Electricity	0.0208 (±0.0033)	0.0302 (±0.0081)	0.0505 (±0.0153)	0.0100 (±0.0143)
Fuel	0.1503 (±0.0349)	0.1141 (±0.0237)	0.0738 (±0.0114)	0.1287 (±0.0385)
Lubricants	0.0072 (±0.0017)	0.0049 (±0.0012)	0.0025 (±0.0002)	0.0099 (±0.0124)
Fertilizers[1]	0.1273 (±0.0449)	0.0543 (±0.0200)	0.0017 (±0.0004)	0.1836 (±0.0463)
Herb.- pest.[1]	0.2341 (±0.0895)	0.0405 (±0.0102)	0.0019 (±0.0005)	0.0321 (±0.0170)
Seeds	0.5063 (±0.2018)	0.1124 (±0.0286)	0.0305 (±0.0073)	0.0429 (±0.0140)
Feedstuffs	–	0.3375 (±0.0568)	0.5006 (±0.0311)	0.4514 (±0.1593)

[1] Annual average of the whole crop rotation.

Table 7 shows the difference concerning the role of production factors related to the type of farm and the importance of economic assessment of energy required for production factors. On non-mixed farms in Viterbo, the three main production factors (as expressed by the selected input/output AFIs) are fuels (0.92), fertilizers (0.17) and seeds (0.14), in terms of energy, while in monetary terms they are seeds (0.50), herbicides–pesticides (0.23) and fuels (0.15). These values show that there is strong discrepancy concerning the assessment of resource transformation efficiency when the evaluation is carried out in energy or monetary terms. According to the above-mentioned values, 92 units of fuel are required in order to produce 100 units of output on non-mixed farms when measured in joules (energetic units) but only 15 units are required when measured in euros (monetary units).

On mixed farms in Viterbo, the three main production factors are feedstuffs (0.48), fuel (0.44) and fertilizers (0.17) if the transformation efficiency is measured in energy terms, and feedstuffs (0.34), fuels and seeds (0.11) when measured in monetary terms.

On dairy farms in Viterbo, the three main production factors are feedstuffs (1.09), fuels (0.58) and electricity (0.24) when measured in energy terms, and feedstuffs (0.50), fuels (0.07) and electricity (0.05), when measured in monetary terms. On dairy farms on Terceira Island, the three main production factors are feedstuffs (0.77), fertilizers (0.41) and fuels (0.40) when measured in energy terms, and feedstuffs (0.45), fertilizers (0.18) and fuels (0.13) when measured in monetary terms. The energetic efficiency analysis of dairy farm systems both in Viterbo and on Terceira Island shows that the main production factor is feedstuff.

Discussion

Despite the presence of some common features such as volcanic soil and market-oriented organization, the agroecosystems of the two ecoregions in question have some fundamental structural and functional differences (Table 4), depending on their climate and history (e.g., in Viterbo Province the presence of low anthropized

ecological infrastructures close to the fields, such as small woods, hedges or rivers, has positive effects on the agro-environment such as mechanical barriers, biological filters and biological reservoirs).

Generally speaking, the main difference between Viterbo and Terceira dairy farms is that milk production is the only output for Terceira farms (specialization) and the main output for Viterbo farms (diversification) is characterized by both crop and livestock production. The difference in MP (4.1 versus 7.3; in Terceira and Viterbo, respectively) is related to the difference in the climatic and management conditions between the two areas and probably due to the performance of the Frisona breed.

On Terceira farms, the use of direct energy input is practically half compared with Viterbo and this is mainly due to the less intensive farm livestock management. On the other hand, the use of indirect energy inputs (fertilizers, pesticides, etc.) is significantly higher on Terceira farms compared with Viterbo (0.76 versus 0.60, respectively) and this is due to the need for Terceira farms to supply livestock and fodder crops with external energy sources. In fact, the simplified crop rotation, the relatively high presence of alien weeds in imported feedstuffs and seeds, and the low diffusion of legume crops such as forage crops, creates the need for using chemicals (herbicides and pesticides) and encouraging the use of fertilizers (especially nitrogenous fertilizers) and feedstuffs. In monetary terms, there is less difference in the amount and use of direct–indirect inputs of energy required between Viterbo and Terceira farms: the monetary distribution of direct (0.19 versus 0.17) and indirect (0.81 versus 0.83) energy inputs on the dairy farms shows similar values. The main reason for this situation is the low cost of direct energy on Terceira Island compared with Viterbo (€0.37 versus €0.87 kg^{-1} of diesel, respectively) (Table 3), which is due to the Portuguese and European economic support policy in the Azores. A different economic weight of the same energy resource is enough to establish significant agro-ecological differences between the two dairy farm systems in Viterbo and on Terceira Island.

In Viterbo, the feedstuff value is higher due to the fact that the farmers purchase larger amount of this produce from the market. This means that the environmental cost of grain crop cultivation (i.e., the ecological footprint) is 'loaded on other places and/or countries in the world' where feedstuff is produced and exported. Terceira Island is more affected by these environmental costs because more fodder crops are grown on its farmland by providing external inputs. As a consequence, animal breeding is on the increase which is based on feed purchased on the market. The availability of nitrogen from industrial sources makes the presence of legume fodder in rotations unnecessary[36]. Without poliannual crops in rotation there is no control over weeds and other harmful biological agents and treatments with chemicals are necessary. In the future, it would be useful to evaluate the possibility of implementing alternative renewable energy sources on dairy farm[35] and remodeling farms in a more sustainable way[37].

Currently, the human consumption of food of animal origin, which is frequently under scientific discussion, negatively affects the environment (e.g., greenhouse gas emissions), human health (e.g., saturated fatty acids) and ethical aspects. Vieux et al.[38] suggested that changing the structure of the diets by reducing the consumption of animal-based products is probably not an effective approach for significantly reducing greenhouse gas emissions. In addition, they[38] observed that the environmental and human health effects resulting from the reduction of meat consumption are not always both positive. Therefore, the iso-caloric replacement of animal-based products with fruit and vegetables may simultaneously have a positive effect from a heath point of view and a negative effect from an environmental point of view.

The concept of farm as a 'system' composed of various components to be organized in a sustainable way, in accordance with socio-economic and environmental goals, was already scientifically established in the 19th century by Cuppari (1862)[39]. Crops and livestock were regarded as the complementary components of a mixed farm, due to the integration of the grazing and detritus chains which allows the farm to operate as a self-sustaining agro-ecosystem. Draghetti (1948)[39] was one of the first Italian scholars in the 20th century to clearly define the model of circulation of matter-energy on a farm and to carry out the experimental trials at the farm level in order to quantify the benefits of the integration of crop and animal husbandry for yield increase and soil fertility maintenance[40]. The results of this study are partially in contrast with the above agroecological concept as the input requirement is higher on mixed farms. This is due to the fact that the grazing and detritus chains are stressed in both areas since farms buy feedstuff rather than calibrate the number of animals raised on the available fodder area. Furthermore, the detritus chain is not improved and the use of chemical fertilizers can produce a negative impact on the state of the environment (i.e., nitrogen pollution).

However, there are some limitations concerning this study since it only focuses on the energetic and monetary flows of food production without bearing in mind other important aspects such as nutritional (i.e., conversion of sugars, fats, protein, vitamins, amino acids and other elements), and social (e.g., farmer education, inclusion of women, unemployment) aspects.

In the attempt to find useful ASIs, energy and monetary results appear not to offer a single coherent account of farming systems sustainability also because the bio-physical and socio-economical readings of the situation are not yet in agreement. This explains why there is an urgent need to discover an environmental accounting method capable of integrating the ecological and economic aspects[12].

Recently, when facing new problems of increasing risks for human health and the environment, and due to the recent development of conventional agriculture, the European agricultural policy has been promoting new models of sustainable agriculture that have their roots in the principles of both traditional agriculture and the modern science of agroecology[41–43]. Therefore, it is essential to promote a greater use of sustainability indicators in policy and management decision-making processes[34] translating into practice the use of ASIs, also in order to be able to assess their real validity.

Conclusions

This study identified some key components for achieving the sustainable development of agroecosystems in the two ecoregions in question. One component would be to increase the autonomy of farms, so that strategic decisions can be taken at the farming level in order to maintain productivity without compromising the long-term sustainability of the farm. This flexibility in the management of agroecosystems may be particularly important in the larger context of a free market economy and enforcement of (inter)national agricultural policies.

To assess the sustainability of agriculture and the provision of environmental services, it is essential to balance the complex interactions between the environmental, economical and social dimensions of agroecosystems. We suggest that particular attention should be paid to how the farm's structural characteristics relate to its agroecosystem performance at regional level, while considering the sustainability of agroecosystems.

With the development and use of ASIs, agroecological research is becoming part of the structure of civil society, improving its role of scientific service for public utility. The step of introducing ASI as a scientific topic of research at academic level is extremely relevant in order to develop a new transdisciplinary science of sustainability. Building on this foundation, there is now a tremendous opportunity to advance a new global scientific research paradigm—the generation and implementation of the science of sustainability.

The political recognition of agriculture as a multipurpose activity in society has created the need to invest more intellectual and financial resources into research for monitoring and measuring sustainability conditions in agriculture.

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A critical review and re-assessment of theories of smallholder decision-making: a case of conservation agriculture households, Zambia

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Abstract

Different theories have been posited that try to explain the decision-making process of smallholders especially regarding the adoption of new technologies or new agricultural techniques. The objective of this paper is to review and re-assess the dominant household production theories to explain the decision making of smallholders practicing conservation agriculture (CA) in the southern, eastern, and central provinces of Zambia. It also discusses the potential role of CA toward economic development. It finds that the CA smallholders studied did not aim to maximize profits but tried to secure household consumption from their own production before any other considerations in risky and uncertain environments. Their response to economic incentives was contingent on minimizing risks associated with securing a minimum level of livelihood and investing into local forms of insurance. This paper concludes that the ability for CA to contribute to rural livelihoods and economic development would depend on how adequately the factors that hinder smallholder agricultural development in general are addressed.

Key words: farm/non-farm linkages, profit maximization, risk aversion, utility maximization

Introduction

There is no consensus in the literature about how to explain the behavior of smallholders in relation to household production choices. At one extreme are the theories premised on smallholders' inclination toward profit maximization, whereas at the other extreme are propositions that they are irrational, unmotivated by profit and unresponsive to economic incentives. Some supporters of the latter view have gone so far as to cite smallholders' conservatism as being responsible for their low agricultural productivity and poverty. The perceptions of the behavior of smallholders have implications in that development interventions and policy prescriptions are based on their predicted responses or lack thereof.

If it is assumed that smallholders act rationally, then it follows that growth in agricultural productivity can be achieved by increasing factor availability and providing new technologies[1]. On the other hand, if it is assumed that they are irrational, a different set of interventions is planned and implemented. The success of the interventions would therefore depend on the validity of the underlying assumptions about the behavior of their intended recipients, in this case, the smallholders. In my view, these diametrically opposed positions both suffer from the same shortcoming of theorizing without context. They are premised on assumptions that do not hold in many of the cases to which they are extended. I adapt Elli's[2] definition of peasants to define smallholders as households which derive their livelihoods mainly but not exclusively from agriculture, predominantly utilize family labor in farm production, are characterized by a partial engagement in input and output markets, and are both producers and consumers of agricultural goods and services. The term peasant is avoided due to the pejorative connotations usually associated with it in preference for the more neutral term, smallholder.

According to FAO[3], conservation agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while enhancing the resource base and the environment. It is conceptualized as a set of agronomic

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practices encapsulated in three principles namely: (i) minimal mechanical soil disturbance through zero or reduced tillage; (ii) maintenance of a permanent soil cover through the use of cover crops, intercrops, or mulching provided by crop residues or other organic materials; and (iii) diversification of crop species grown in sequences and/or associations[4,5]. Owing in part to the wide diversity in the agro-ecological, economic and institutional landscapes of sub-Saharan Africa the actual practices of CA adopted across the sub-region vary tremendously. For instance, the operationalization of the principle of minimum mechanical soil disturbance can either be zero/no tillage or reduced tillage; performed manually, using animal draft power or tractors.

The variants of manual zero/no and reduced tillage systems commonly employed in southern and eastern Africa are use of the jab planter, dibble stick and the digging of planting basins.[6] The jab planter and the dibble stick are used to plant seeds directly into the soil without any tillage while the digging of planting basins entails up to 30% of the soil is inverted. For those farmers with access to animal draft power, ripping, the making of furrows along which seeds are placed; or animal traction direct seeding systems are used. The tractorized variant also takes two forms, zero/no tillage or reduced tillage.

There are variations in the sizes of planting basins and accompanying cultural practices regionally. In West Africa , planting basins, termed 'zai', in Burkina Faso, 'tassa ' in Niger, are 20–30 cm in diameter and 10–15 cm deep[7]; in Zimbabwe, the planting basins are 15 cm deep, 15 cm wide, and 15 cm broad[8] whereas in Zambia, they are $30 \times 20 \times 15$ cm. A corollary of zero or reduced tillage under CA is increased weed pressure and use of herbicides. Under zero/no tillage systems, herbicides are exclusively used for weed management whereas both herbicides and mechanical weeding are employed in reduced tillage systems. Differences in the practice of CA are also through whether crops are rotated sequentially or intercropped; the legume crops grown; whether and what cover crops are used; if crop residues are used to provide the soil cover or organic materials are imported into the fields to act as mulch[5].

Recently, there have been increasing calls for the integration of nitrogen-fixing trees with CA systems to have what is termed as conservation agriculture with trees (CAWT) or evergreen agriculture. CAWT reduces run-off and soil erosion, improves the physical, biological and chemical properties of the soil; combines the synergies of rapid improvements of livelihoods from CA with the longer term but sustained crop productivity and environmental resilience derived from nitrogen-fixing tress[9]. It builds on the indigenous knowledge of minimum-tillage farming techniques, traditionally practiced by many African communities in the past[10]. Underlying all of these CA principles and practices is the notion that agriculture should nourish and enhance the natural biological processes that support soil fertility, nutrient cycling and hydrological cycling. These ecosystem services, in turn, benefit farmers by boosting crop yield, reducing (but not excluding) the need for external inputs, increasing farm profitability and reversing land degradation[5].

CA has been, and continues to be, promoted in Zambia on the assumption of the rationality of the smallholders. It is assumed that the current and persistent low productivity of smallholders in Zambia is caused by lack of access to appropriate technology and inputs, and a lack of knowledge of yield-improving sustainable agricultural practices like those packaged as CA. Reduced tillage practices promoted among CA farming households are the digging of planting basins and ripping. Planting basins are dug along carefully measured rows in a $0.9\,m \times 0.7\,m$ matrix using a specially designed hoe called a *Chaka* hoe[11]. Ripping is performed using a plow-like animal-drawn implement called a ripper to make 15–20 cm deep furrows in which seeds are planted[12]. The soils between the planting basins and ripped lines are left undisturbed. Zero tillage planters with configurations suited for oxen, horses and donkeys are being trialed in Zambia[13].

Mechanized systems, although not yet common in Zambia, involve the use of tractors attached with disks and harrows, and direct drill planters. Hoes, cultivators and herbicides are used for weed removal before and after crops are planted. Herbicides such as glyphosate (*N*-(phosphonomethyl) glycine, 41% active ingredient), paraquat (1,1′-dimethyl-4,4′-bipyridinium dichloride), and atrazine (2-chloro-4-ethylamino-6- isopropylamino-1,3,5-triazine) are used. Manure and mineral fertilizers are prescribed at application rates of $4\,t\,ha^{-1}$ and $325–550\,kg\,ha^{-1}$ [14] for the planting basin system and $4\,t\,ha^{-1}$ and $200–500\,kg\,ha^{-1}$ [11] for the ripped systems, although the prescribed rates are rarely attained by smallholders. Crops are planted into the planting basins and ripped furrows after either manure or mineral fertilizer has been placed at the bottom. Other agronomic practices promoted as part of the CA package in Zambia are dry-season land preparation and early planting; planting of the legume tree *Faidherbia albida* within fields; and frequent weeding (4–6 times).

The objective of this study was to document smallholder CA farmers' practices and household decision making, and assess these in light of the main household decision-making theories. There is an implicit assumption by CA experts and promoters that once the smallholders are shown the agronomic and economic benefits of CA, their profit maximizing calculus would automatically lead them to adopt it. No study has been conducted to assess whether such assumptions are valid with regards to CA smallholders in Zambia. I hypothesized that CA smallholders in the studied areas do not aim to maximize profits. Rather, they try to secure household consumption from own production first before any other considerations. This study shows that the non-adoption of CA by numerous smallholders who have clearly seen its

Table 1. Selected agro-ecological descriptions and sample sizes of the study areas.

Study area	Location	Crop growing period (days)	Mean annual rainfall (mm)	Population density (persons km^{-2})	Panel study	Sample size	
						Interviews	Field assessments
Mumbwa	Central Zambia	100–140	804	10.3	160	32	109
Petauke	Eastern Zambia	100–140	932	39.4	160	36	101
Chipata			1033	67.6			
Katete			983	60.4			
Sinazongwe	Southern Zambia	80–120	789	21	160	61	298
Monze		100–140	732	40.4			

agronomic and economic benefits suggests that factors or considerations other than, or in addition to, profit maximization may be at play. The phenomenon of partial adoption of CA, where smallholders adopt CA but only practice it on some of their fields is the norm. CA smallholders report higher yields and incomes from their CA fields even as they continue to farm substantial proportions of their land in the conventional way. Although they do respond to economic incentives, their responses are contingent upon 'safety first', minimizing risks associated with securing a minimum level of livelihood and investments by investing into local practices that serve as insurance. This may explain why they only partially adopt CA, which despite its productivity improving benefits, is still susceptible to the vagaries of climate and market failures. They also employ a range of livelihood diversification strategies aimed at dealing with the risks and seasonality that they have to endure over the course of a year.

The paper is informed by my field experiences and numerous discussions with CA and non-CA smallholder families, local leadership of rural communities in the southern, central and eastern provinces of Zambia, experts on CA and agricultural development in general, academicians and scientists working with smallholder families from all over the world and extensive literature review on the subject. I review a range of theories on household production choices and try to interpret the empirical evidence obtained from my own field work and from literature in the context of these theories. I use concepts from Ellis's[15–17] Rural Livelihood Diversity in Developing Countries to think through the choices and activities of the smallholders under study.

Methodology

Overview of the study areas

Fieldwork was conducted in Sinazongwe, Monze, Mumbwa, Petauke, Katete and Chipata Districts. These are semi-arid areas with average annual rainfall of between 600 and 1000 mm (Table 1). The seasonal rainfall is received between November and May, while the rest of the months are dry. The rainy season is characterized by inter- and intra-seasonal variations. The soils found in Sinazongwe are generally of low agricultural potential and are further limited by a seasonal lack of adequate water. The soils in the other districts are highly weathered, and of high agricultural potential[18]. Sinazongwe and Monze are located in the Southern Province of Zambia; Mumbwa is in the Central Province, whereas Petauke, Katete and Chipata are in the Eastern Province. Smallholder farming in the study areas is mainly rain fed and characterized by, *inter alia*, climate-related risks and uncertainties such as floods and droughts.

Except for Mumbwa, the population densities of the study areas were higher than the national average of 17.3[19]. According to FAO[20] these areas have a potential to support population densities of 201 persons per km^2 under low-input and up to 500 persons per km^2 under high-input agriculture. This suggests that the areas are currently underpopulated. Typically, a farming household had in excess of 20 ha of land under its direct control but only about 10–20% of this land is cropped in any one season[21]. Similar to other areas where land is relatively abundant, the size of cultivated land is not determined so much by limited access to land as by limited household access to labor for cultivation[22].

Mixed farming systems dominate, with most households engaged in both crop and livestock production. The most dominant crop grown is maize (*Zea mays*). The study areas are found in the southern half of Zambia referred to as the maize belt. This is a reflection of the ubiquitous production and consumption of maize in the region. Other crops traditionally grown include sorghum (*Sorghum bicolor*), groundnuts (*Arachis hypogaea*), cassava (*Manihot esculenta*), sweet potatoes (*Ipomea batatas*), soybeans (*Glycine max*), cowpeas (*Vigna unguiculata*), common beans (*Phaseolus vulgaris*), cotton (*Gossypium hirsutum*), tobacco (*Nicotiana tabacum*) and sunflower (*Helianthus annuus*).

Livestock mainly reared are cattle, goats, sheep and pigs. Poultry are also common, with local breeds of free-ranging chickens, guinea fowls and ducks being preferred. Mixed farming systems have led to the development of local norms pertaining to grazing for livestock. After harvest and on a date set by the traditional leadership (either chief or headman) fields become communal grazing grounds for livestock, which are then allowed to freely roam around the communities, whereas

before they are either restricted to kraals or tethered near the owners' homesteads. In this way, the livestock owners benefit through increased access to crop residues for their livestock while the owners of the fields benefit from the replenishment of soil nutrients through the dung that is dropped as the livestock graze. There is also an understanding that the oxen-owning households reciprocate by lending their oxen to the households without oxen at least once during land preparation (P.H. Nyanga, personal communication, 2012).

Data collection

Several field visits were made to the study areas beginning from February 2008 to January 2011. Primary data were collected through a 4-year panel survey that started with 640 respondents; 129 semi-structured interviews; field assessments; numerous informal interviews and talks; two focus group discussions; key informant interviews; observations; and attending field days. Field assessments included observing and recording of labor use during four farming operations, namely land preparation, planting, weeding and harvesting, over two complete farming seasons. Two focus group discussions were conducted with CA farmers representing all the four tillage methods under consideration. The discussions centered on household decision making pertaining to farming activities such as tillage system, crop choice, access and allocation of inputs.

Data analysis

The questionnaire survey and field assessments data were analyzed using independent sample *t*-test, Analyses of variance (ANOVA) and descriptive statistics were calculated using statistical software MINITAB 15 for personal computers[23], R Studio[24] and PASW/SPSS 18[25]. The statistical tests were conducted at a probability level of $P \leqslant 0.05$.

Theory and Literature Review

Profit maximization theories

The profit maximization theories, epitomized by work from scholars such as Schultz[26], Lipton[27], Stiglitz[28] and others, argue for the smallholder mode of production as profit maximizing. The households are treated as farm businesses whose main aim of production is to allocate resources in order to maximize profit. They assume that the resource and production conditions confronting the smallholders are homogeneous, and that the markets for land, labor, capital and input/output products are fully competitive[29]. In his seminal 'efficient but poor' hypothesis, Schultz[26] posited that allocative efficiency was mostly high in smallholder agriculture in the context of the prevailing technical possibilities and of the factor and product–cost relationships. He elucidated that there were comparatively few significant inefficiencies in the allocation of the factors of production in traditional agriculture. His definition of traditional agriculture was that it was a 'particular type of economic equilibrium at which agriculture gradually arrives over a long period, provided that: (1) the state-of-the-art remains constant, (2) the state of preference and motives for holding and acquiring sources of income remains constant, and (3) both of these states remain constant long enough for marginal preferences and motives for acquiring agricultural factors as sources of income to arrive at an equilibrium with the marginal productivity of these sources viewed as an investment in permanent income streams and with net savings approaching zero'[26] (pp. 29–30).

The defining characteristic of traditional agriculture is thus that the physical and economic environments, as well as preferences, have been stable for long enough that farmers have arrived at an equilibrium in which they optimize at the margins in their resource allocation and investment decisions[30]. What follows is that disparities in economic behavior between farmers in poor and high-income countries arise not from any differences in economic motivation but rather from constraints faced by farmers, both resource constraints and constraints arising from existing institutions[31]. Hence, to raise the productivity of traditional agriculture, farmers must have access to new information and high-payoff inputs. Schultz also assumed that smallholders in developing countries responded positively to price incentives[32]. He refuted the notion that farmers in developing countries were poor because of cultural characteristics such as a lack of work ethic, lack of understanding of the idea of saving, or general ignorance of how to make best use of their resources[30]. Schultz[26] further argued that low income levels in developing country agriculture were a result of the low productivity of the available factors of production, not of inefficiencies in their allocation. The implication of this assertion was that outside experts could not help farmers improve productivity merely by suggesting a re-allocation of the available factors of production and it was therefore important to invest in education to facilitate the diffusion of new factors that could enhance productivity[30].

By experimentation over time, Schultz argued, where the state-of-the-arts has not changed and where the environment is inherently risky, farmers learn how to allocate the resources at their disposal in a manner that is consistent with their own interests, that is, in an efficient manner[31]. Sauer and Mendoza-Escalante[32] contended that Schultz's hypothesis had important implications with respect to the long-term effectiveness of an individual development strategy applied to smallholder farming. If farmers are reasonably efficient, then an additional increase in efficiency requires the usage of more productive inputs and/or the application of a more productive technology to shift the production frontier upwards. If on the other hand, current inputs and/or technology could be

used more productively, an improvement in the institutional setting that includes input markets, infrastructure endowment, available extension systems, management, and training services should be targeted to increase efficiency at the farm level.

Criticisms of Schultz's hypothesis have been leveled at his strict definition of a traditional agriculture and for failing to consider the implications of market failures for his hypotheses. Lipton[27] observed that Schultz's hypothesis was only applicable for individual utility maximization under perfect competition. In the presence of market failures, even if farmers allocate their resources efficiently from each individual's point of view, there may still be collective inefficiencies. At the group or collective level, therefore, the efficient but poor hypothesis may fail[30]. The proposition that smallholders are efficient in a purely neoclassical profit maximizing sense requires such strict assumptions about the competitiveness of the markets in which smallholders operate, that these are rarely likely to pertain in the smallholder populations from which the samples are drawn[2]. However, Ellis[2] argued that a great deal of evidence, especially on the responsiveness of smallholders to changes in relative market prices between crops, reveals a strong element of economic calculation on the part of smallholders everywhere.

Ellis proposed what he called *conditional* profit maximization instead. Smallholders maximize profits subject to (1) trade-offs with other goals, (2) resource constraints, and (3) the working of markets. Since the process of decision making of a smallholder family involves both production and consumption aspects, other economists have argued that profit maximizing theory tends to ignore a major side (i.e., consumption side) of the smallholder household decision process[33].

Another criticism of the profit maximization theory is that its assumptions are rarely likely to pertain to African smallholder societies. Many case studies have shown resource and production conditions in smallholder societies to be highly heterogeneous. Land in African smallholder societies is traditionally not subject to sale, and its allocation and use are guided by cultural, social and political relations[30]. Labor is not freely available for sale in many smallholder societies, and work is primarily carried out by family labor. There are clear divisions of labor within the household which further limit the competitive allocation of labor. The availability of capital in smallholder societies is clearly limited and competitive capital markets are not developed[29].

Utility maximization theories

These theories encompass the dual character of smallholder households as both families and enterprises and thereby take into account the consumption side of smallholder decision making[34]. Lipton[27] argued that utility maximization places emphasis on survival under conditions of uncertainty. Under conditions of imperfect knowledge (uncertainty) there is not a single marginal physical product for each factor, but a probability range within which the actual marginal physical product for any factor will be in a given year, and the range may be quite great. Under conditions of uncertainty, the smallholders, instead of profit maximizing, seek survival algorithms.

Chayanov[33] posited that the goal of any smallholder household was simple reproduction rather than profit maximization. He proposed that the interaction of consumption and production within the household caused a unique form of decision making, which sets smallholders apart from any other kind of production unit under capitalism. Chayanov argued that the smallholder economy could not be studied by applying profitability oriented capitalist economic principles. His utility maximization model involves a trade-off between the drudgery of farm work and the income required to meet the consumption needs of the household. According to Friis-Hansen[29], Chayanov argued that the smallholder household, using its own labor force, would apply it to agricultural production according to its internal equilibrium. This equilibrium is determined by equating the household demands and needs with the drudgery involved in meeting them.

Using a concept of consumer/producer ratio, Chayanov[33] analyzed the effect of changing household structure during the life cycle of a smallholder household on production and income. He then postulated that the intensity of farming or the use of family labor is a function of the ratio of consumers to workers in the family and that economic differentiation among smallholders in terms of farm size is more a measure of relative family size than differential economic success. Criticisms leveled at the utility maximization theories are that their sphere of analysis is limited to the household, and the theories can therefore not say anything about the development of society as a whole. They also treat the household unit as a single decision-making unit and do not take into account gender relations, division of labor and smallholders' external relations[29].

Theories on risk-averse households

These focus on the trade-off between profit maximization and risk aversion. Smallholders are reported to exhibit risk aversion in their decision making[35,36] and to be risk-averse out of necessity because they have to secure their household needs from their current production or face starvation. There is no room for aiming at higher income levels by taking risky decisions[37]. A risk-averse household prefers a smooth consumption stream to a fluctuating one, which in contexts of incomplete capital markets or underdeveloped institutional arrangements, entails a low-risk portfolio choice of productive activities. Innovative behavior, particularly in agriculture, involves risk and uncertainty.

Using a new technique, input or crop represents risk taking and uncertainty-bearing because by virtue of its newness there is no previous experience upon which to predict the outcome[38]. Because those at the lower end of the income and wealth distribution apply not profit maximization, but a survival algorithm, they will not tend to innovate, and will not receive the gains from innovative behavior[38]. Risk preferences are influenced by the resource constraint and capital market imperfections faced by decision makers. Thus, differences in preferences may be due to differences in access to institutional arrangements that enable households to pool risks across time. Risk, along with asset-poor initial conditions, may contribute to making small farm households inefficient and persistently poor[39]. Households first opt for safety and from the safe alternatives, they choose based on expected utility and possibly expected income.

According to Popkin[40] many of the norms and procedures of smallholder societies are embedded in considerations of subsistence and survival; the village is not only a ritual and cultural unit, but is also an important part of smallholder economic life as a source of rights and resources. Smallholders are concerned with uncertainty when evaluating economic strategies. They prefer strategies with low but certain returns to strategies with high but uncertain returns.

Role of smallholder agriculture in economic development

The role of smallholder farming in agricultural development remains highly debated. Collier[41] argued that smallholder farmers in Africa were ill-suited to the challenges of contemporary agricultural development, lacking scale, knowhow and access to supply chains. He criticized the long-term preferences of donors and governments in Africa for small farms and their reluctance to support large-scale farming as a disservice to the continent. Favoring small farmers, he posited, was romantic but unhelpful. Collier and Dercon[42] contended that fast labor productivity growth is what is needed for large-scale productivity improvements but smallholders and the institutions to support and sustain them are weak agents for labor productivity growth in Africa. In response to this criticism, authors such as Wiggins[43] have countered that records show the cases of smallholder success in Africa, both at district levels and for countries. Byerlee et al.[44] observed that small farmers can be efficient and innovative as seen in Asian green revolution but also in Africa as well when given the chance.

Others have argued that when smallholders increase production and productivity, the rural poor gain. Food security is as much about incomes and access as food supply; that is, agricultural development through smallholders can do much to raise the incomes of the poor and their access to food[45].

The Future Agricultures Consortium organized an e-debate on the topic and the contributors made the following arguments; small farms have advantages in managing labor as household labor is self-supervising in effort and diligence. This leads to more intensive use of labor and consequently higher output per hectare on smaller farms than larger ones. Small farmers may be better stewards of natural resources, conserving biodiversity and safeguarding the future sustainability of agricultural production[45]. When countries are poor and agrarian, with people effectively trapped on the land, focusing on small farm development can reduce poverty, provide jobs, and constitute a safety net for those with few other assets than their access to land. For others, one of the roles of small farm development is to prevent premature migration[46]. Displacing smallholders in developing countries would create a kind of social, political and economic chaos[47]. Similarly, Deininger and Byerlee[48] recently argued that smallholders have an intimate knowledge of local soil and climate, often accumulated over generations, that gives them an advantage in tailoring management to local conditions and the flexibility to quickly adjust management decisions to site, seasonal and market conditions.

Although the large diversity among nations in their physical endowment, cultural heritage and historical context precludes any universally applicable definition of the role that agriculture should play in the process of economic growth, certain aspects of agriculture's role appear to have a high degree of generality because of special features that characterize the agricultural sector during the course of development[49]. Agriculture, as the dominant sector of an underdeveloped economy can and should make a contribution to the capital required for overhead investment and expansion of secondary industry. The sheer size of the agricultural sector as the only major existing industry points to its importance as a source of capital for overall economic growth. Rising net cash incomes of the farm population may be important as a stimulus to industrial expansion[49]. Lewis[50] and Hirshman[51] saw the role of agriculture in economic development to be as a supplier of labor for the expanding urban industries.

Mellor[52] extended Lewis's arguments and espoused that agricultural growth creates demand for locally produced non-tradable items necessary for rural development. Mellor and Johnston[53] pointed out that not only does agricultural growth provide food for the rural households it promotes employment in non-agricultural sectors by increased demand for non-agricultural consumer goods. For the case of Africa, Vogel[54] claimed that an agricultural demand-led industrialization strategy was a strong development option as agriculture was the primary source of factors that could be invested in the region's emerging industrial sector. Agriculture does not take place in isolation from the other sectors of the economy but is more or less closely intertwined with them in a matrix of interdependence.

Table 2. Average maize yields (t ha^{-1}) from conservation and conventional agriculture fields.[1]

CA	Conventional agriculture	Study
5.2[a]	1.8[b]	Umar et al. 2011[59]
4.4[a]	1.7[b]	Umar et al. 2012a[60]
3.6[a]	2.1[b]	Umar 2012b[61]
5.5[a]	3.6[b]	Thierfelder and Wall, 2009[62]

[1] Means in the same row followed by different letters were significantly different at $P \leqslant 0.05$.

Delgado et al.[55] among others have demonstrated that agricultural development has vital linkages with other sectors. Mellor[56] postulated that promoting growth linkages in agriculture resulted in the highest multiplier effects. Davis et al.[57] identified two types of farm/non-farm linkages. These are production and expenditure linkages. Agricultural production needs inputs while its products are used as inputs elsewhere. Households deriving income from one type of activity are likely to spend that income on products of other activities. Local entrepreneurs and wage earners use incomes from the sale of non-farm products to buy food and other agricultural outputs. They also provide inputs for the agricultural sector.

CA has been placed within this theoretical framework as an agricultural system that can contribute to economic development. By increasing labor productivity and gross margins, CA has the potential to increase smallholders' incomes and improve household food security[58]. With time the poorest CA households are expected to graduate from being mere subsistence producers to selling a substantial part of their production through increased cash cropping and improve their cash income earnings. This links to the non-farm sector through their purchases of non-farm consumer goods, and purchase of agricultural inputs.

In the rest of this paper, I discuss the above theories in relation to my observations and analysis of smallholder farmers who were practicing CA in Zambia. I then comment on the extent to which the theories explain the results of my analysis of the practices and perceptions of the CA farming households studied.

Results and Discussion

Practicing of CA in Zambia: a deductive analysis

The practice of CA in the study areas did not seem to be based on profit maximization but rather several considerations were made. I make this assertion based on my own research on the CA smallholders in the study areas and also from critical review of the literature. I present the reasons for this assertion in the sub-sections below.

Partial adoption of CA systems. The superiority of yields from CA fields compared with conventionally farmed fields was reported by all the 129 households that participated in the semi-structured interviews and from the 2-year field assessments during this study; and other studies on CA in Zambia (Table 2)[59–62]. This view was also put forward in the focus group discussions, informal discussions and by most key informant interviewees. Yet all but one of the CA households continued to practice CA on only a portion of their total cultivated areas and allocated between 30 and 50% of their cultivated areas to CA. Allocating all their cultivated areas to CA would have increased their crop yields, total crop production and crop incomes. However, the CA households have several considerations when they select agricultural systems at the beginning of any particular farming season. One of these is choice of crop. There is a perception that some crops perform well in particular tillage systems. Therefore, once the decision has been made to engage in the production of a crop, the preferred tillage system for that crop will be used. For instance, sweet potatoes and cassava are characteristically grown on ridges and are perceived to be unsuitable for growing using CA tillage systems currently adopted in Zambia.

Timing and drudgery. Another consideration made is the labor requirement and the timing of the land preparation for the farming system. The recommended ideal period for digging the basins is the post-harvest dry season. CA promoters contend that this enables labor-constrained households to spread their labor over a longer period. It also allows CA farmers to plant with the first effective rains in November, the beginning of the rainy season in Zambia. The combination of basins, precise input application and early planting results in higher yields. However, many CA households did not follow these prescriptions despite knowing their agronomic and subsequent economic benefits. They preferred to wait until the beginning of the rainy season before commencing to dig basins. They explained that basin digging was a very labor-demanding activity characterized by drudgery. This drudgery was exemplified in their perception of having done much more work than they actually did (Table 3).

Households overestimated labor use on basin preparation by 42% but underestimated it in the hand hoe system by 37%. While the field assessments did not reveal any significant differences in labor use between basins and hand hoe systems, the farmers thought that the basin system required significantly more labor. Farmers also perceived their labor use to have been similar for ripping and plowing when, in fact, they had expended significantly less labor when ripping compared with plowing (Table 3). Field assessments and farmer perceptions converged in their conclusion that labor used for weeding was similar in the basin and hand hoe systems. This similarity seemed to suggest that households expended all the labor they could access at the time, and not a reflection

Table 3. Comparisons of actual labor use and perceptions in different tillage systems.[1]

		Manual tillage		Animal draft powered	
		Basins	**Hand hoe**	**Ripped**	**Plowed**
Field assessment (person days ha^{-1})	Land prep	24^{a} (40.1)	21.2^{a}	0.8^{a}	3.8^{b}
	Weeding	44.4^{a} (34.3)	48.4^{a} (39.7)	52.9^{a} (85.0)	32.1^{b} (30.9)
Farmer perception (person days ha^{-1})	Land prep	34^{a} (25.9)	13.4^{b} (9.2)	7.8^{c} (10.3)	8.8^{c} (11.2)
	Weeding	47.0^{a} (41.4)	48.8^{a} (38.4)	43.0^{a} (45.2)	38.7^{a} (32.3)
Frequency of seasonal hand weeding	Actual	2.2 (0.6)	2.2 (0.8)	2.5 (0.5)	1.9 (0.3)
	Recommended	4	2	4	2

Note: Values in parenthesis are standard deviations. Comparisons were made for the manual and animal draft powered systems separately.
[1] Means in the same row followed by different letters were significantly different at $P \leqslant 0.05$.

Table 4. Area under different tillage systems over four farming seasons.

		2006/ 2007	2007/ 2008	2008/ 2009	2009/ 2010
Average area/ household	Basins	0.67	0.68	0.51	0.52
	Hand hoe	1.1	0.98	0.8	0.7
	Ripping	1.0	1.03	0.96	1.2
	Plowing	2.1	2.4	1.7	2.1

of the labor requirements for the two systems, which are different.

Ideally, CA fields must be weeded four or five times per season, but this was not achieved (Table 3). There was divergence between actual labor use and farmers' perception for the ripped and plowed systems with farmers reporting similarity when in fact ripping required more.

Basin digging was engaged in only for long enough to till an area of land sufficient to meet the families' consumption needs and rarely more than that. Area under basins per household that had adopted this tillage system averaged 0.67 and 0.68 ha during the 2006/2007 and 2007/2008 farming seasons, respectively, but reduced to 0.51 and 0.52 ha during the 2008/2009 and 2009/2010 farming seasons, respectively (Table 4).

The households were either unwilling or unable to expand area under basins much beyond the area cultivated. I argue that basin digging was adopted as a safety first food security strategy and not for profit maximization. Moreover in line with Chayanov's[33] assertions, I further argue that the CA households did not push the practice of basin digging beyond the point where the possible increase in output was outweighed by the drudgery of the extra work. Chayanov[33] had further observed that each family struck a rough balance between the degree of satisfaction of family needs and the degree of drudgery of labor.

Drudgery aversion also explains the CA household members' behavior. Most of them waited for the rains to soften the soils before they engaged in any tillage operations despite the yield losses that resulted from late land preparation and planting. They also only worked for a few hours per day, usually from early in the morning to mid-morning or midday. They spent the rest of the day on non-farm activities such as chatting with friends, resting, drinking beer, and attending to household and community responsibilities; *anything but farming*. They preferred engaging in such activities to continued digging of basins despite the higher production that would result from having larger tracts of land under basins.

CA farming operations and livelihood strategies. The failure by most CA households to engage in dry-season basin digging seemed also to be related to their livelihood diversification strategies, which entailed their engagement in non-farm activities during the dry season. The CA farmers engaged themselves in economic and social activities during the post-harvest period such as trading, fishing, rethatching of huts, carpentry, masonry, craft making, preparations and attending of traditional harvest ceremonies, weddings and travel to urban areas[59]. Smallholder farming in Zambia is a precarious enterprise influenced by uncertainties that are biophysical, institutional and economic. The biophysical uncertainties are typified by the unimodal rainfall whose distribution is unknown at the beginning of the season.

The large variances in the rainfall amounts and distribution within and between seasons have spurred the development of risk aversion behavior among smallholders. Smallholder CA farmers minimize risk by having a combination of tillage and cropping systems. Nyanga[63] also noted the diversification of tillage systems among CA farmers in Zambia and suggested that rather than seeing CA as an overall superior agricultural system, farmers perceived CA as an additional option, among many, for addressing their food security problems.

Area under CA after flood incidences. The average area under basins per household reduced during the 2008/2009 and 2009/2010 farming seasons, which were characterized by above normal rainfall that resulted in floods[64]. Basins became waterlogged and farmers responded by backfilling them and making ridges around the crops. The farmers reported that although this action greatly

Table 5. Economic analyses for four tillage systems from field assessments and farmer perceptions.

		Basins	Hand hoe	Ripping	Plowing
Field assessments	Gross margins (US$ ha^{-1})	465.4	7.3	105.9	−56.9
	Total variable costs (US$ ha^{-1})	367.4	314.4	511.1	424.1
	returns to labor (US$/person-day)	5	0.9	3.1	0.9
	Quantity of fertilizer applied (kg ha^{-1})	88.7	75	203.4	216.9
Farmer assessments	Total variable costs (US$ ha^{-1})	212.9	46.2	115.1	435.3

disturbed the soil, it was necessary for crop survival but complained that it increased their labor burden. This shows that farming households are responsive to unexpected changes in their environment and act to minimize crop losses, even if that means going against the recommendations of CA experts. The flooding episodes also exacerbated weed pressure. Field observations confirmed very high weed infestations in fields that had been flooded. This seemed to be a disincentive to the expansion of a tillage system whose success is premised on its attribute of conserving water during periods of moisture stress and therefore recommended for low rainfall areas. The CA households responded by re-allocating less land to basins and slightly more to ripping during the 2009/2010 farming season, as ripped fields had not been besieged by waterlogging to the same extent.

Profitability comparisons for CA and conventional systems. Ripping had higher gross margins than plowing (Table 5), basin digging was also much more profitable than its conventional agriculture equivalent, hand hoeing. It must be noted that family labor was given a shadow price and treated as a variable cost during the calculations of gross margins. Smallholders themselves do not cost family labor in this way. Their assessments of total variable costs was thus less than the actual for all tillage systems except plowing, as in their calculations they did not include the cost of labor that was not paid for.

Farmers persisted with the less profitable plowing as it was a deeply embedded practice, which has been tried and tested over many generations. In southern and central Zambia, plowing is also associated with the tribal identity of the dominant tribes of these areas. Plowing was, for instance, perceived as what *Tongas* do'. Being *Tonga* is conceptualized as including the use of oxen and mould board plow for tillage. Ripping does not yet have the same cultural connotations. Basins were profitable during periods of normal and below normal rainfall. However, during seasons of above normal rainfall, they became waterlogged and resulted in yield losses.

Plowing and hand hoeing result in yield losses during periods of below normal rains. CA households therefore prefer the lower but more stable yields that result from the diversification of tillage practices as opposed to complete conversion to CA tillage systems. This process of livelihood diversification is not unique to the study areas but is common to many poor communities whose lives are characterized by uncertainty. Ellis[16] contended that seasonality explained many of the patterns of diversity in rural household incomes, especially those involving on-farm diversity and off-farm agricultural wage earnings. He further argued that as both risk and market imperfections abound in the rural economy, income instability, and consumption smoothing are real problems confronted by households, and therefore an important motive for income diversification associated with seasonality is to reduce income instability.

CA households in Zambia and production choice theories. The observed behavior of the studied CA households agrees with the utility maximization theories in that households are more interested *not* in profit maximization but in maximizing their utility, be it through assurance of home consumption, avoidance of drudgery and engagement in non-farm activities. Lipton[27] argued that under conditions of imperfect knowledge or uncertainty, smallholders seek what he termed as 'survival algorithms' and not profit maximization. Scott[65] in a similar vein posited that the smallholder cultivator seeks to avoid the failure that will ruin him rather than attempting a big but risky killing. This is exemplified in this case by smallholders not knowing the future price of their crops and the local rainfall distribution at the beginning of the farming season when decisions about which crops to grow are made. When it comes to maize, for instance, the central government through its agency called the Food Reserve Agency (FRA) sets the floor price of maize grain after harvest. Smallholder farmers therefore have no way of knowing whether it would be profitable to grow maize beforehand.

Smallholder farming in Zambia is quite unique for its dominance of maize, not only in terms of inputs allocated to maize growing but in the collective farmers' and policy makers' mindsets. Successful farming seasons are conceptualized as 'bumper' maize harvests. In south, central and eastern Zambia, farming is maize and maize is farming. Not only is maize the single most important staple crop, but it is also a culturally and politically important crop. The first considerations made when it comes to farming at the start of the farming season by all typical smallholders in southern Zambia is to produce maize, how much maize to produce, and what resources to allocate to maize production. The maize is grown first and foremost for household consumption. Depending on the resources the household is able to command, decisions on growing cash crops then follow while the production of locally adapted

food crops, either as intercrops or in own fields, goes without saying.

The diversity and quantities of crops grown by a household is also a reflection of its command over the relevant resources. Those who can afford to, grow all kinds of crops for the many different household uses. In the south-eastern part of Zambia the saying '*pa khomo apa mpamwana alirenji* ' whose literal translation is 'this household has everything, what can a child cry for?' is a reflection of the importance of growing for own consumption and the desire to be as self-sufficient as possible especially with food resources. All households grow the must-have crops such as maize, groundnuts, pumpkins, sorghum, cowpeas and so on; whereas the better endowed ones venture into cash crops, horticulture and a higher diversity of other crops. The better endowed households also use more purchased inputs such as mineral fertilizers, hybrid seed, pesticides, hired labor and labor-saving technologies. They are also able to respond to economic incentives and adopt new innovations as they can afford to take risks in a way that poorer households cannot.

Smallholder CA households and risk. Duflo[66] argued that poverty changes the set of options available to individuals. A poor person is more likely to be risk averse if he has limited access to resources/insurance since shocks are particularly painful if one has very little to buffer them. He may thus not be an efficient farmer because the efficient choice would be too risky. Ellis[17] argued along similar lines and posited that risk aversion results in farming practices designed to increase family food security rather than to maximize profits. A trade-off is made between livelihood security and economic efficiency. Smallholders' risk aversion inhibits the diffusion and adoption of innovations, which could improve the output and incomes of smallholder farm families. In the areas studied, risk aversion was manifested by the focus on producing for own consumption; the piecemeal adoption of CA; and diversification of tillage systems and livelihood strategies.

Risk aversion also resulted in the delayed application of basal fertilizer. Instead of applying the basal fertilizer before planting as prescribed by agronomists, most households reportedly waited until after the shoots had emerged. Focus group discussants asserted that they did not want to risk their hard-earned fertilizer by putting it in the ground when they were not sure that it would rain in good time and the maize seed would germinate and the shoots would emerge. They also delayed their planting until they were sure that the rainy season had effectively started. These two risk-averse strategies resulted in sub-optimal crop yields. Hagblade and Tembo[67] and CFU[14] estimated that Zambian smallholders lost 1–2% of their yield for every day they delayed their planting after the first planting opportunity. Scott[65] argued that living close to the subsistence margin and subject to the vagaries of weather and the claims of outsiders, a smallholder household has little scope for the profit maximization calculus of traditional neoclassical economics.

While most smallholders studied responded to economic incentives, their environment characterized by market and government failures limited or conditioned their responses . In Mumbwa District, they responded to the higher soybean prices by allocating larger areas to soybean production as they cut down on cotton production. Cotton companies offered ZMK1400 kg^{-1} (US$0.3 kg^{-1}) while soybeans were sold at ZMK3500 kg^{-1} (US$0.7 kg^{-1}). Most farmers complained of low cotton prices offered by the cotton companies in the area.

Focus group discussants and probing from individual farmers during the administering of the semi-structured interviews revealed that although velvet beans (*Mucuna pruriens*) was known to be a good cover crop and excellent at nitrogen fixation, only 14% grew it. The most common complaint leveled against its production was that there was no market for it. Government failures to provide public goods such as roads and other communication infrastructure increased the transaction costs on the part of the smallholders and reinforced market failures. The roads leading to the communities in the study areas were in a grave state of disrepair and most were impassable at the peak of the rainy season. In such an environment, farmers opt to focus on producing for own consumption instead of producing high-value crops that would generate the cash for buying food.

CA smallholders may not be efficient but poor, as espoused by Shultz[26] but they definitely respond to economic incentives that they perceive as not placing their livelihood options under undue risk. In this regard, the CA farmers in the areas studied responded positively to price incentives by increasing the production of crops whenever the farm gate prices stabilized at levels perceived as high enough to spur the increased production. Other incentives such as provision of input and price subsidies, or even free inputs by technology promoters also elicited responses from the CA households (Table 6).

In the study area, a CA promoter provided sweet potato vines, cassava cuttings, cowpea seeds to CA farmers and stationed extension agents in the study area to closely supervise them. The result was an increase in both the number of households producing these crops and the average quantities produced. There was a reduction in the number of households growing cotton (Table 6). The households that abandoned cotton cultivation complained of the low prices, while those that continued with it revealed that they increased the hectarage under cotton in efforts to maintain stable cotton incomes after the fall in cotton prices. This was reportedly challenging for them as cotton production was labor intensive and required up to five weedings per season. This is as was observed by Ellis[2] that a great deal of evidence, especially on the responsiveness of smallholders to changes in relative market prices between crops, reveals a strong element of economic calculation on the part of smallholders everywhere. This is contrary to the perception that poor smallholders do not respond to economic incentives

Table 6. Average percentages of household crop production and total production for selected crops.

	Percentage of households growing crop in given farming season		Average total production for crop per household (in kg)	
Crop	**2006/2007**	**2009/2010**	**2006/2007**	**2009/2010**
Sweet potatoes	28.1	66.5	442.9 (50.5)	678.7 (88.8)
Cowpeas	24.4	43.3	127.8 (16.9)	133.2 (16.7)
Cotton	36.6	23.7	672.5 (56.7)	790.3 (66.4)
Cassava	2.5	9.8	190.6 (64.8)	303.4 (62.3)
Maize	96.6	98.2	2401 (163)	3245 (280)

Note: Values in parentheses are standard errors.

because they are overly risk averse, due to their culture or are laggards.

CA smallholders were engaged in work-sharing arrangements in which labor was pooled for purposes of helping labor-constrained counterparts meet their labor needs during critical farming periods. For widows without adult males in their households, the help extended to such activities as rethatching of huts and granaries, plowing and ripping, weeding, pre-tillage felling of large trees and other activities on humanitarian or altruistic basis. Local mechanisms also include sharing food, receiving remittances, sending off household members to less affected kin. Patrons, that is, wealthy households that have patron–client relationships with the poorest households, are also expected to help out by providing food to affected clients. These are limited in that most members of the same community are poor. It is difficult for patrons to provide adequate help during calamities that affect a large number of people at the same time, e.g., food shortages resulting from droughts or floods.

Development of such norms is aimed at spreading risk and helping offset resource constraints. Such practices are part of what Scott[65] referred to as the moral economy of the peasant. He distinguished between technical and social arrangements. Under social arrangements he included patterns of reciprocity, forced generosity, communal land and work-sharing. Technical arrangements consisted of seed varieties, planting techniques and timing. These arrangements helped to even out the inevitable troughs in a family's resources which might otherwise have thrown them below subsistence. In a similar vein, Popkin[40] observed that many of the norms and procedures of smallholder societies are embedded in considerations of subsistence and survival; the village is not only a ritual and cultural unit, but is also an important part of smallholder economic life as a source of rights and resources.

In the studied areas, it was common for smallholders to leave their farming at critical periods to go and attend funerals or visit sick kin and friends within or in neighboring villages. Such show of support for one's kin and friends was expected to be reciprocated in the future when misfortune struck one's household. For the very poor households, their mere presence was enough, while the rich patrons were expected to help the affected family meet its material needs. These norms would qualify in Scott's[65] terminology as social arrangements. Technical arrangements in the studied areas included the selection and planting of local landraces, multi-cropping, mixed farming (crop and livestock production) and the like. Focus group discussants reported that the exchange of 10 kg bags of hybrid seed for 10 kg of local seed varieties was common. Abler and Sukhatme[31] observed that aspects of agricultural households' decisions and land tenancy arrangements in developing countries seemingly defy efficient behavior. However, Lipton[27] elucidated that many superficially odd village practices make sense as disguised forms of insurance.

Placing CA in context—its linkages and role in economic development

During the period immediately after harvest, CA households have disposable income from their crop sales which they use to purchase consumer and investment goods. They use part of their incomes to purchase agricultural inputs. Local purchases spur the local economy but are limited by a lack of business entities in the locality. Travel to urban centers is usually necessary for the acquisition of most goods. This minimizes the local linkages between the farm and the non-farm sectors. The severe dearth of critical infrastructure such as all-weather roads, small-scale processing industries, electricity and mobile phone networks also increases the transaction costs. This has, on the one hand, benefited and encouraged the growth of private transporters. The small-scale processing sector is limited to a very small number of the better-off households that own mechanical processors for vegetable oils (groundnuts, sunflower) and milling (maize, groundnuts); and threshers. Blacksmiths forge the blades for traditional hand hoes and the *Chaka* hoes used for digging basins, while local carpenters make the wooden handles for the hoes. The agricultural implements are also stocked in shops in the urban centers.

The dependence on externally procured and expensive inputs and lack of availability of CA implements (rippers,

subsoilers, planters) limits the backward linkages and the expansion of CA activities locally. The minimal development of local markets and high cost of transporting farming produce to larger urban and peri-urban markets has limited the horticultural production, which can potentially create more local linkages. About 30% of the CA households with irrigated fields near rivers were involved in the growing of tomatoes and green vegetables but they complained of unreliable markets, which occasionally led them to sell at extremely low prices locally to avoid the products going to waste. They also complained about the cost of going to the urban centers to purchase agro-chemicals. The potential for CA to contribute to the economic development is there but is currently hindered by the isolation of most of the smallholders and the high transaction costs.

Theorizing on smallholder CA households in Zambia

Smallholder CA households in Zambia live in environments characterized by uncertainty related to the biophysical environment, markets and public goods provision. They deal with the uncertainty both as consumers and producers. They do not aim at profit maximization but at contingent utility maximization. Their practice of farming prioritizes own consumption before other considerations such as deciding whether and what to grow for sale. The amount and type of foods to be produced for own consumption is mediated by the size of the households and the access to needed resources. In response to the pervasive risks and uncertainty, practices and norms aimed at minimizing risk and the adverse effects of calamitous events have been developed and are consciously maintained. These include strong local institutions for reciprocity, labor pooling and communal grazing for livestock during the post-harvest season, among others. Added to these are livelihood diversification strategies. Most smallholders have a diverse portfolio of activities that are engaged in by different household members at different times of the year.

Decisions on whether to adopt CA, and how many of the prescribed practices to adopt and over what area, are made in light of the impact on the whole range of other livelihood strategies engaged in by the household, and also in light of local norms and practices. Certain crops are locally important and always grown for home consumption and other household uses for such crops as pumpkins, millet and sorghum. No profit motives enter into the growing of such crops. Some farmers also grow crops that have been important historically and are integral parts of rituals during traditional ceremonies. For example, other than maize, pumpkins and sugar canes are used during the *Ncwa'la* ceremony of the *Ngoni* people of eastern Zambia; maize, sorghum and millet are important constituents of traditional beer, consumed at community gatherings in all regions. The extent to which CA contributes to the development of both the farm and the non-farm sector will depend to a large extent on the minimization of risks and uncertainty that characterize the practice of CA by smallholders, drudgery, and labor needs of manual CA, and the removal of factors that hinder the strengthening of farm and non-farm linkages.

Conclusion

This paper has argued that contrary to the profit maximizing theories, the CA smallholders in Zambia do not aim at profit maximization but at being able to secure their own consumption in a risky and uncertain environment. This is contrary to the premises of current dominant CA intervention efforts which assume *a priori* that conviction of CA's agronomic and income earning superiority over conventional agriculture systems would motivate smallholders to embrace CA. Given that smallholders face risks and uncertainty, which influence their responses to agricultural innovations, there is a need to take greater cognizance of the sources of risk and uncertainty, which include rainfall, germination, crop prices and other market-related factors. The challenges faced by smallholders when it comes to meeting their livelihood needs and expanding their income earning opportunities hinder productivity improvements, adoption as well as expansion of CA practice. Infrastructural developments would spur economic activity that could impact positively on both farming and non-farming sectors. Development of both backward and forward linkages to the agricultural sector is needed in order to secure whatever gains could come out of the consistent and increased practice of CA. This can be in the form of support to develop local artisanal jobs, processing and storage facilities, communication infrastructure, service delivery and livestock husbandry.

Access to urban markets would be pivotal as this would improve farmers' incomes and prompt a shift to more of the high-value crops, adoption of productivity improving technologies, and more risk-taking behavior. Reductions in the risks and uncertainty faced by CA households would expand the area under CA and other agricultural productivity improving innovations. This would have positive effects on both the forward and backward linkages. Access to resources is important as it affects smallholders' ability to undertake activities and withstand shocks. The CA smallholders have diversified their livelihood strategies as a risk reducing measure. Promoters of CA in Zambia need to adapt it so that it supports the diversification strategies engaged in by the smallholders rather than to counter them. The sociocultural and institutional environment is important and should be factored into project design and implementation strategies. Local contexts affect both constraints and opportunities.

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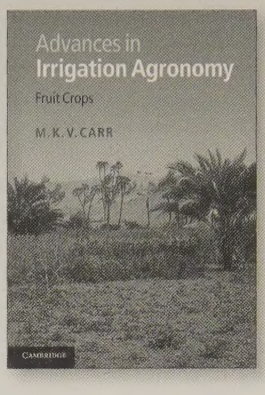

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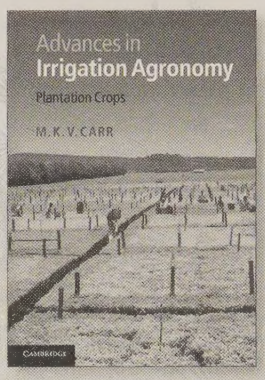

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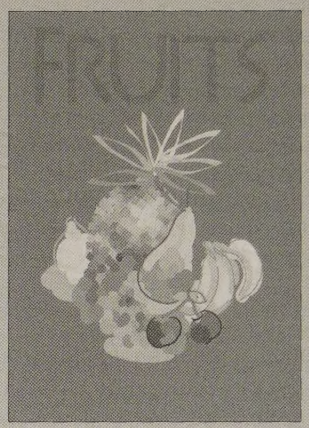

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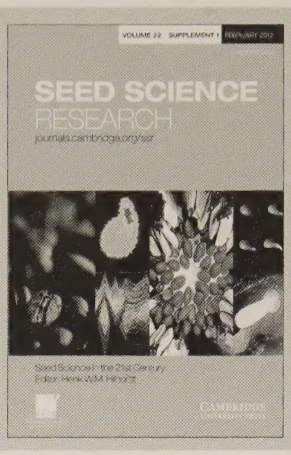

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